Cornering the Higgs with Nets

A CDF search for standard model Higgs bosons produced with Z bosons

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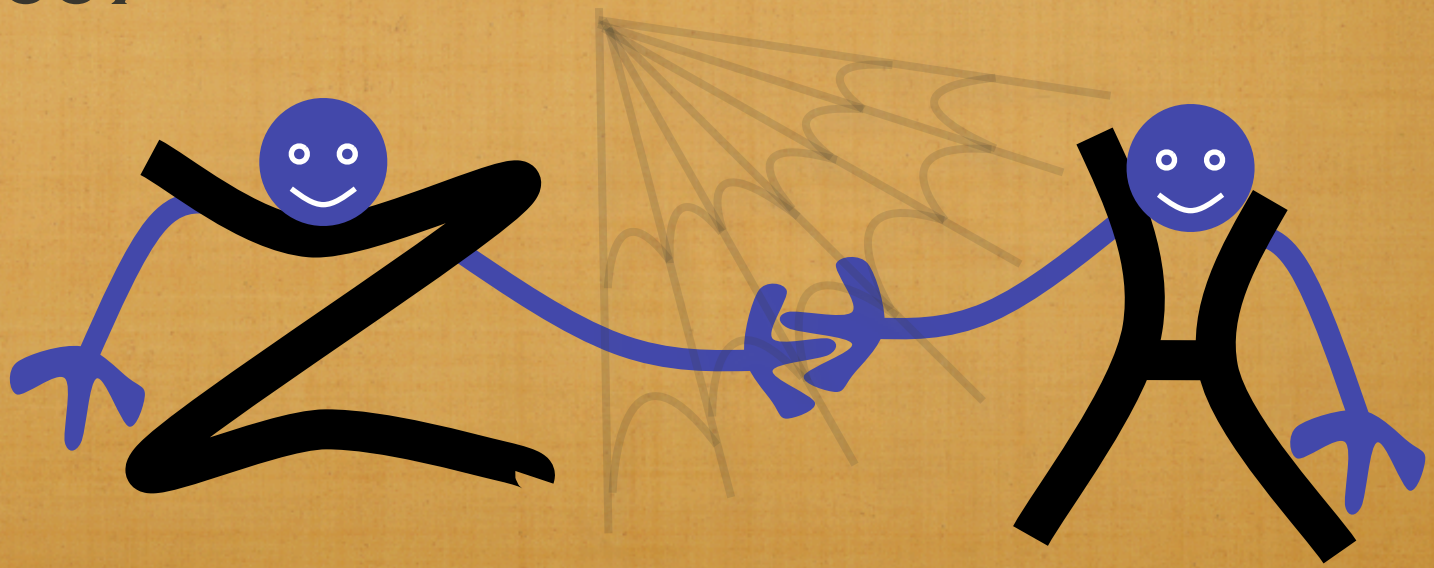
June 8, 2007



Higgs is worth looking for

- In standard model, Higgs mechanism accounts for boson masses
  - Why W & Z bosons massive, but photon massless
- Higgs mechanism gives mass to fermions
  - Coupling of left and right handed particle states to Higgs field in vacuum

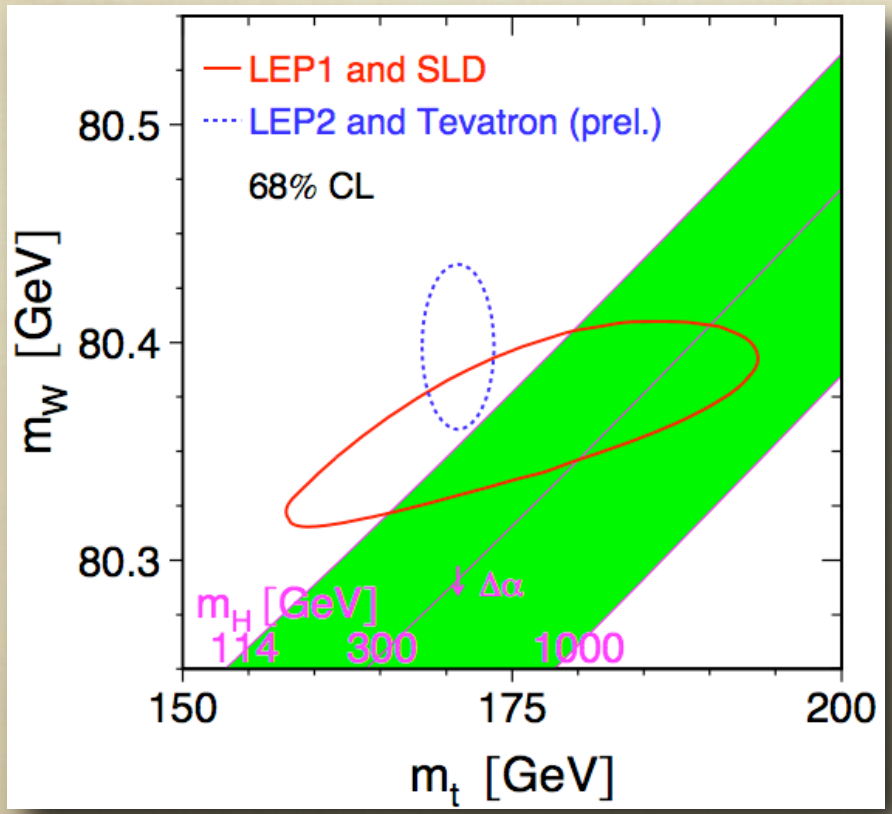
$$m_t = t_R \langle H^0 \rangle t_L$$

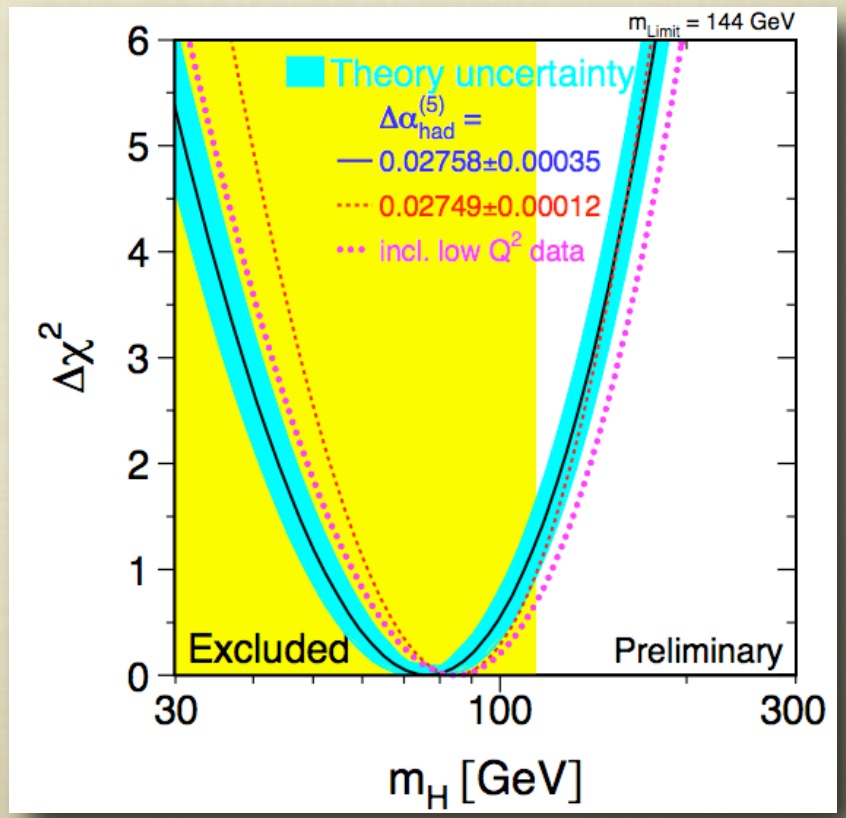
  - Quarks, charged leptons
- Higgs mechanism predicts Higgs boson
  - Discovery potential
  - Last particle of standard model

Experimental Constraints on Higgs

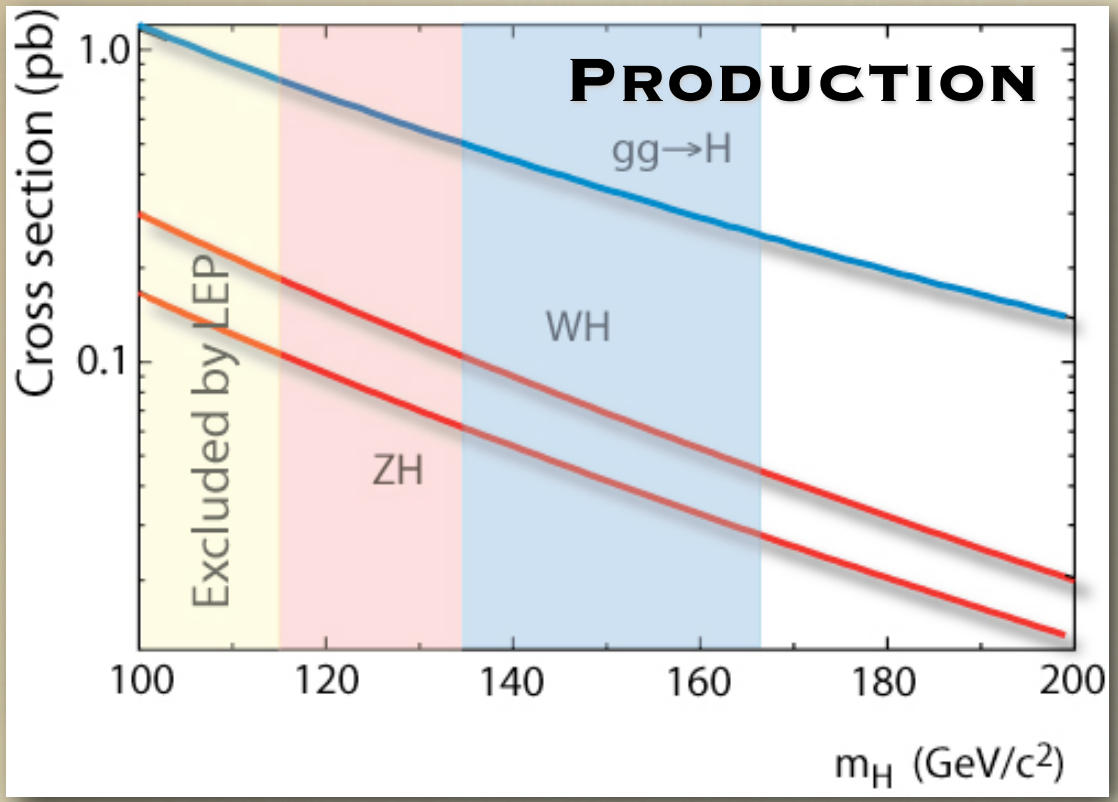
- **Higgs searches ongoing for 30 years**
  - **Direct searches at LEP: $m_H > 114$ GeV @ 95% CL**
  - **Indirect searches :**
    - **Driven by new CDF/D0 $m_t = 170.9 \pm 1.8$ GeV and $m_W = 80.398 \pm 0.025$ GeV**

$m_H = 76\ ^{+33}\ ^{-24}$ GeV, $m_H < 144$ GeV @ 95 % CL





Higgs at the Tevatron



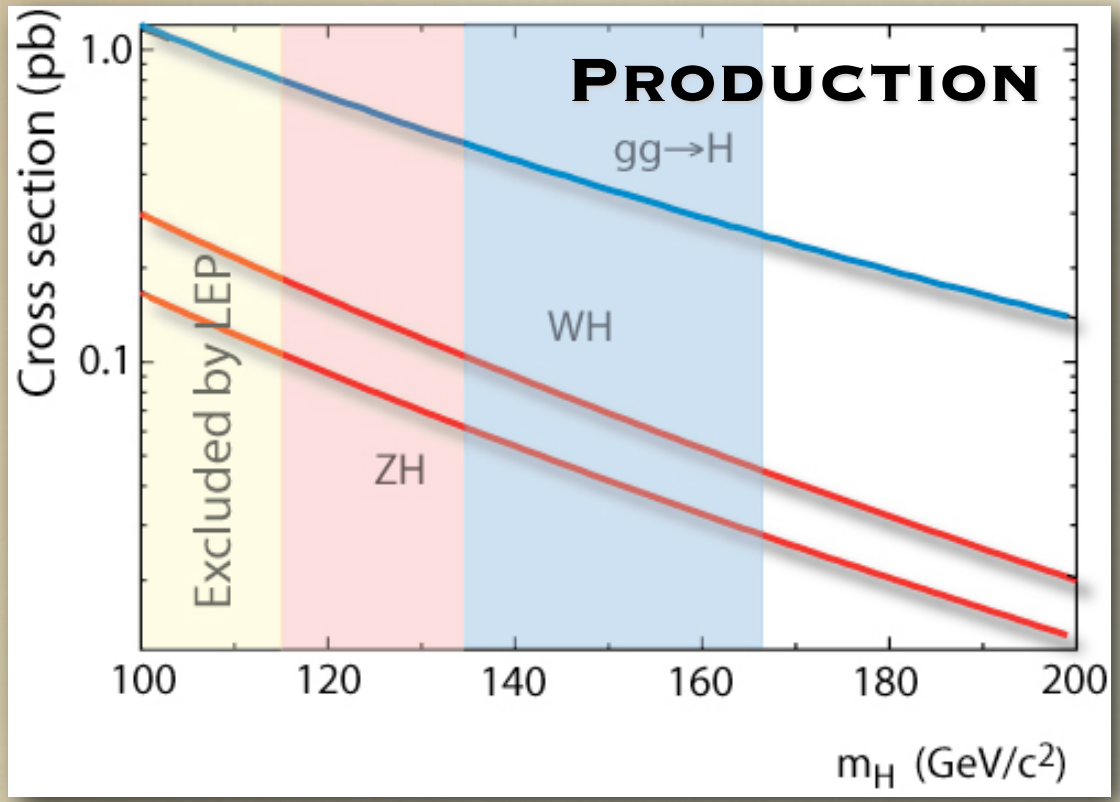
Higgs Production

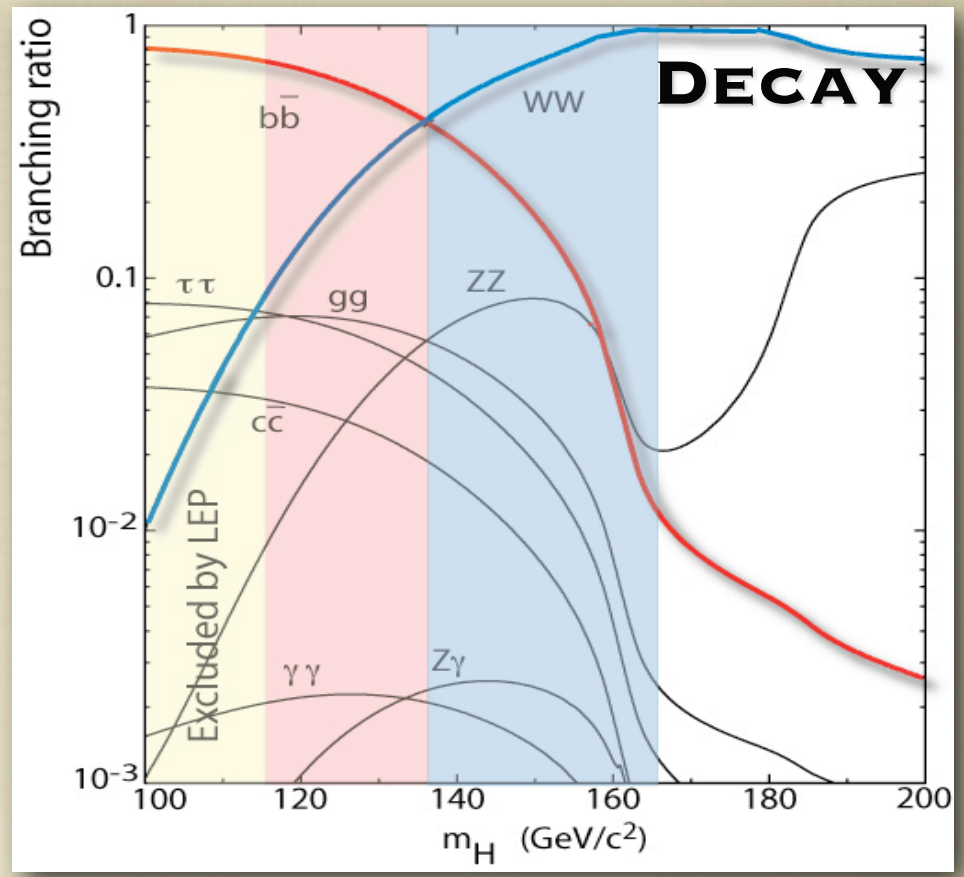
- **< 1 pb**

Compare to

- **12 pb WW**
- **7 pb top pair**
- **3 pb top single**
- **2 pb ZZ**

Higgs at the Tevatron





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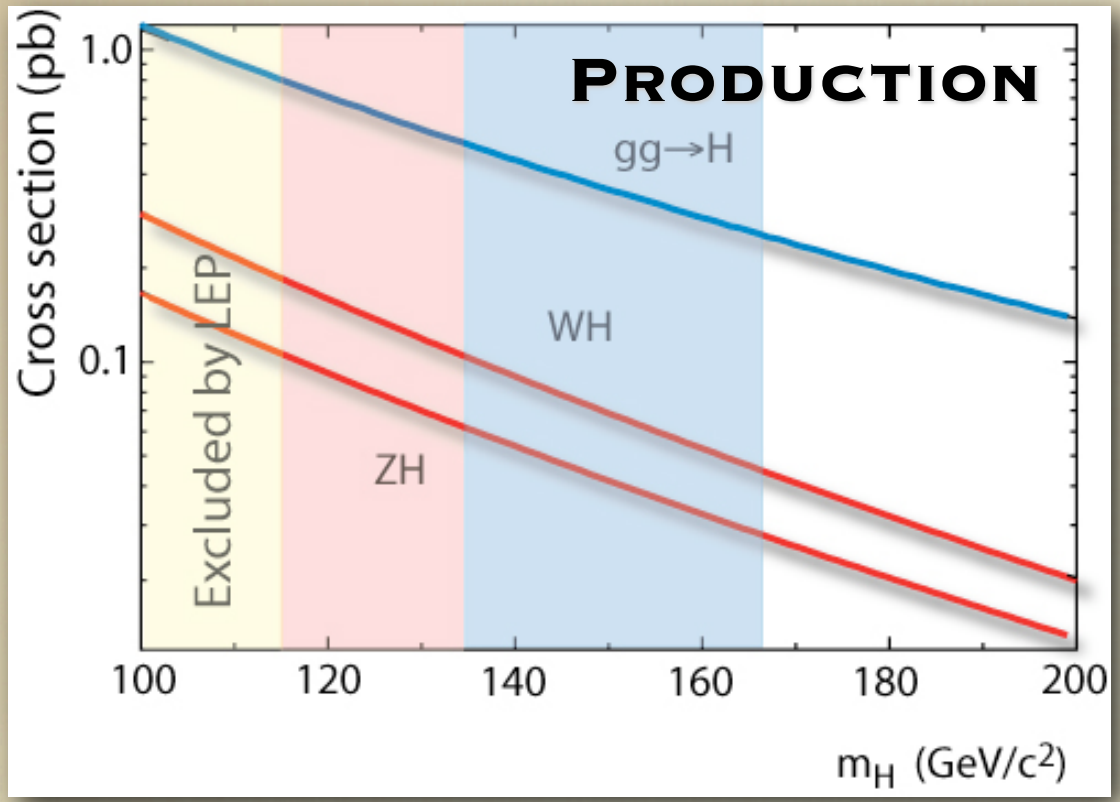

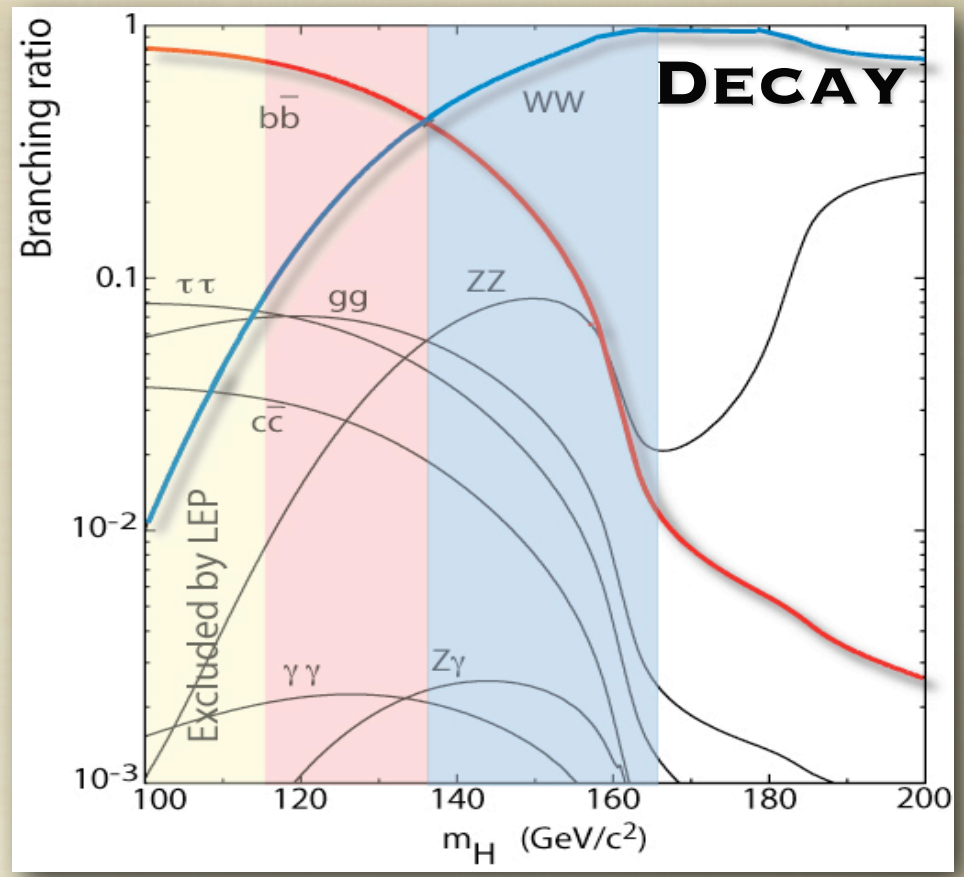

Higgs Production

- < 1 pb

Compare to

- 12 pb WW
- 7 pb top pair
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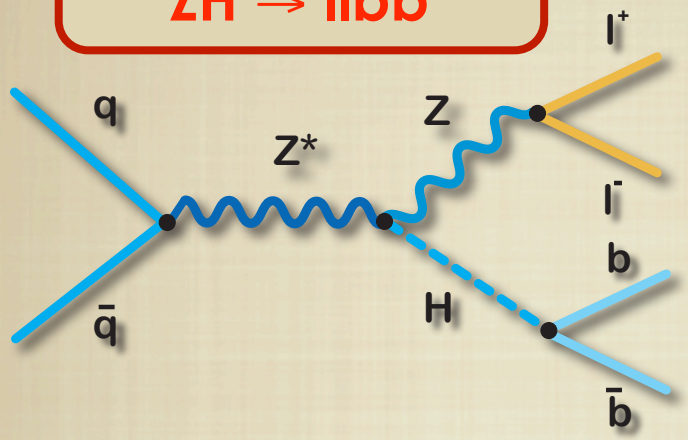
- 2 pb ZZ

Most sensitive Tevatron searches

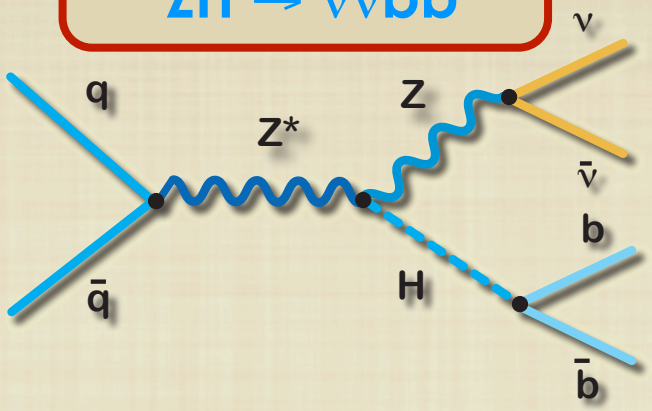
- If low mass (m_H<135 GeV):
  - Production with W or Z
  - Decay to a b-quark pair
- If high mass (m_H>135 GeV):
  - Direct production
  - Decay to a W-boson pair

Higgs at the Tevatron

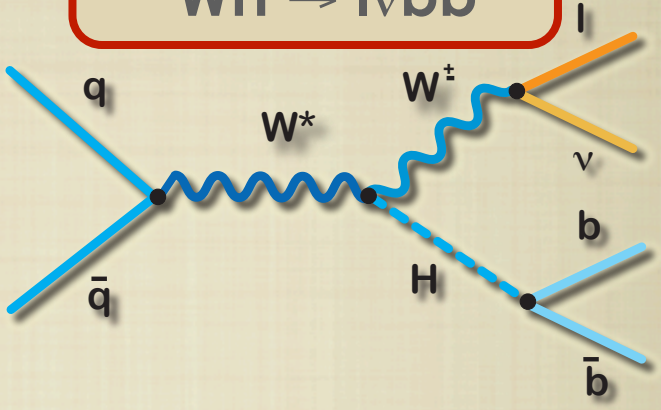
ZH → llbb



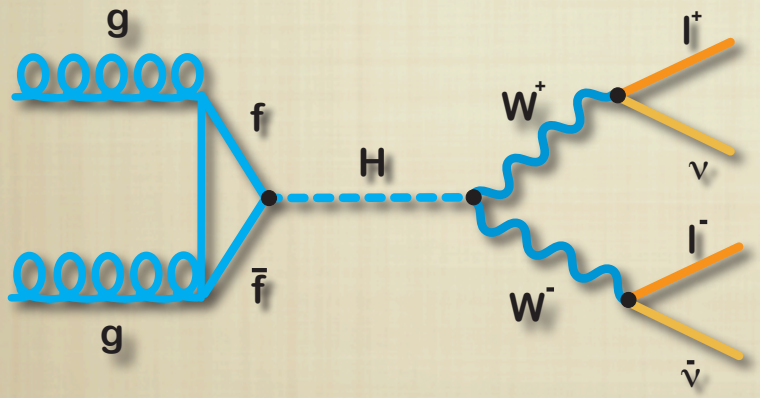
ZH → νν̄bb



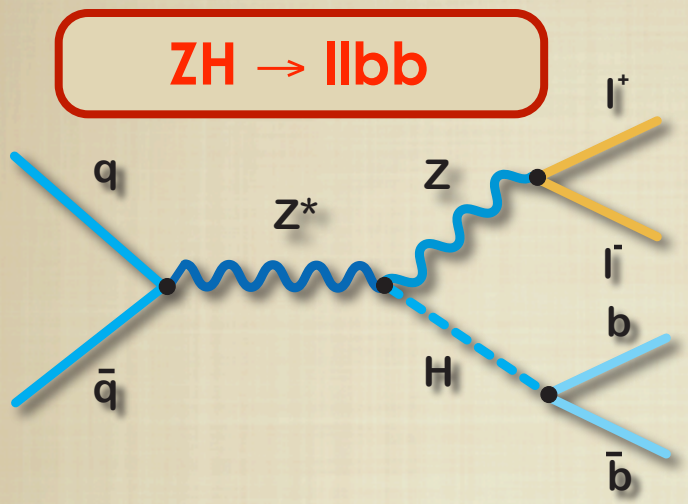
WH → lνbb

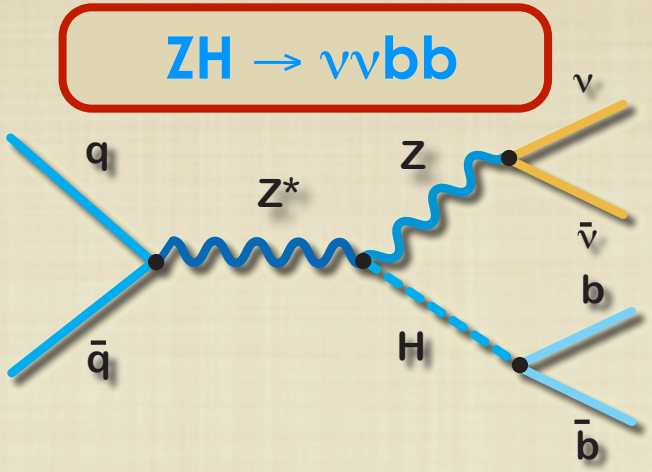


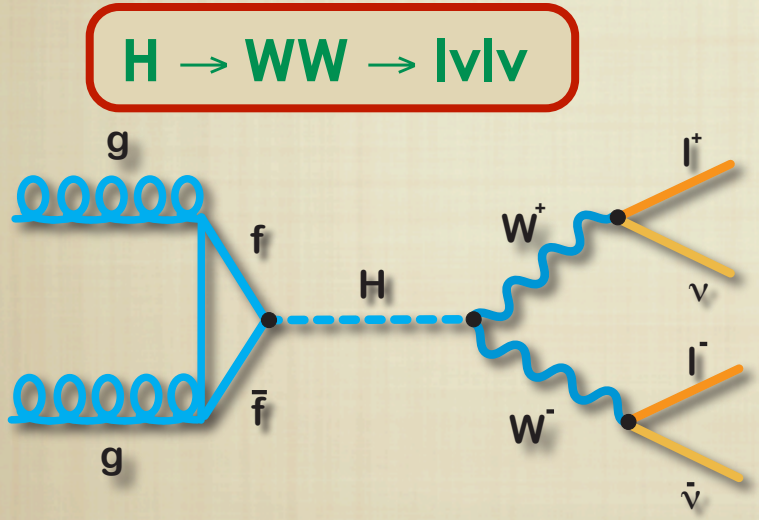
H → WW → lνlν

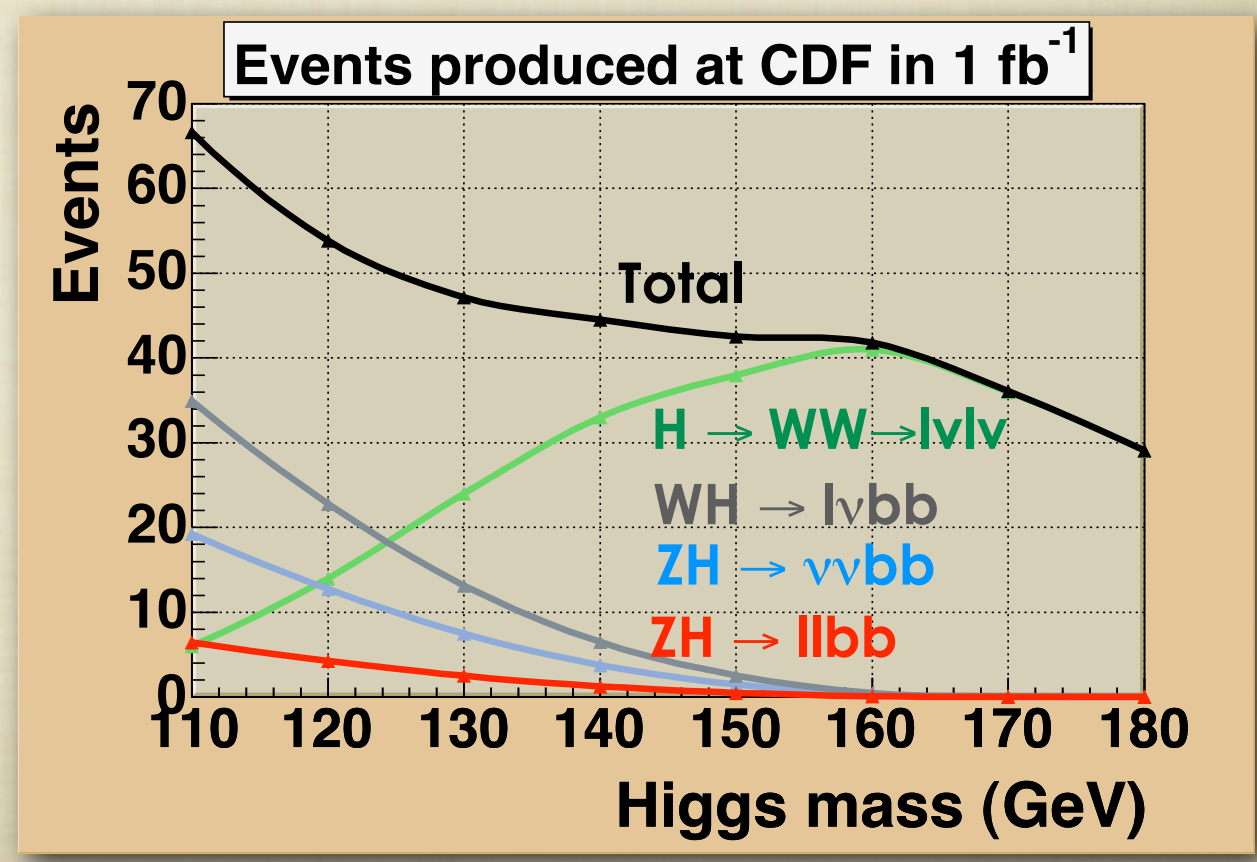


Higgs at the Tevatron

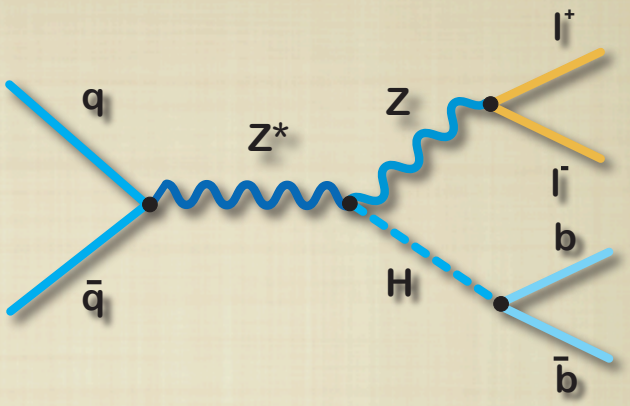








Then why search for ZH → llbb ?

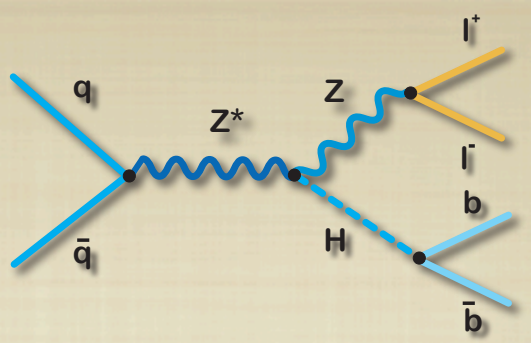


- May have smallest signal yield
- Some benefits
  - Only fully constrained channel
    - No neutrinos
  - Both Z and H resonances
    - Powerful for separating Higgs from backgrounds
  - Fake lepton backgrounds small
    - Hard to fake two leptons with Z mass
- Can we make this channel competitive ?

Outline: Making this channel competitive

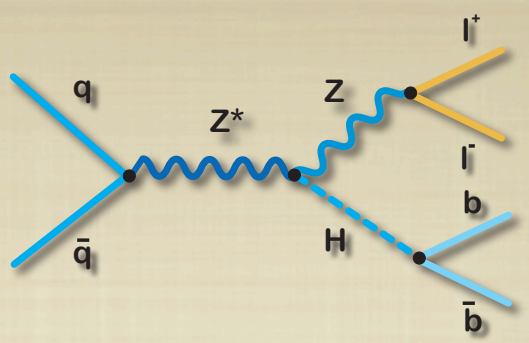
- Retain as much signal as possible
  - Reexamine conventional wisdom for lepton selection
  - Investigate b-parton identification
- Narrow Higgs resonance compared to backgrounds
- Use multivariate approach to get best signal separation from background

What to expect ?



- Ask Pythia what ZH looks like

What to expect ?



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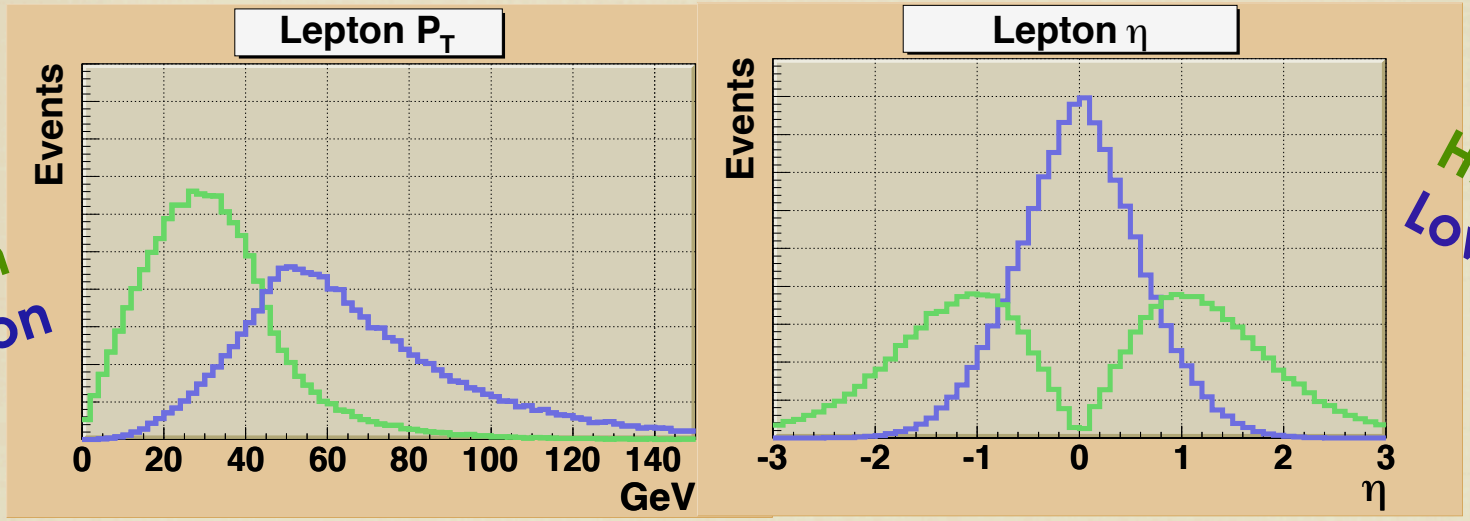
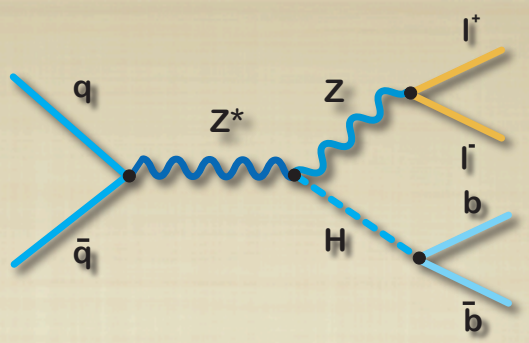


Low p_T lepton
High p_T lepton

High η lepton
Low η lepton

What to expect ?



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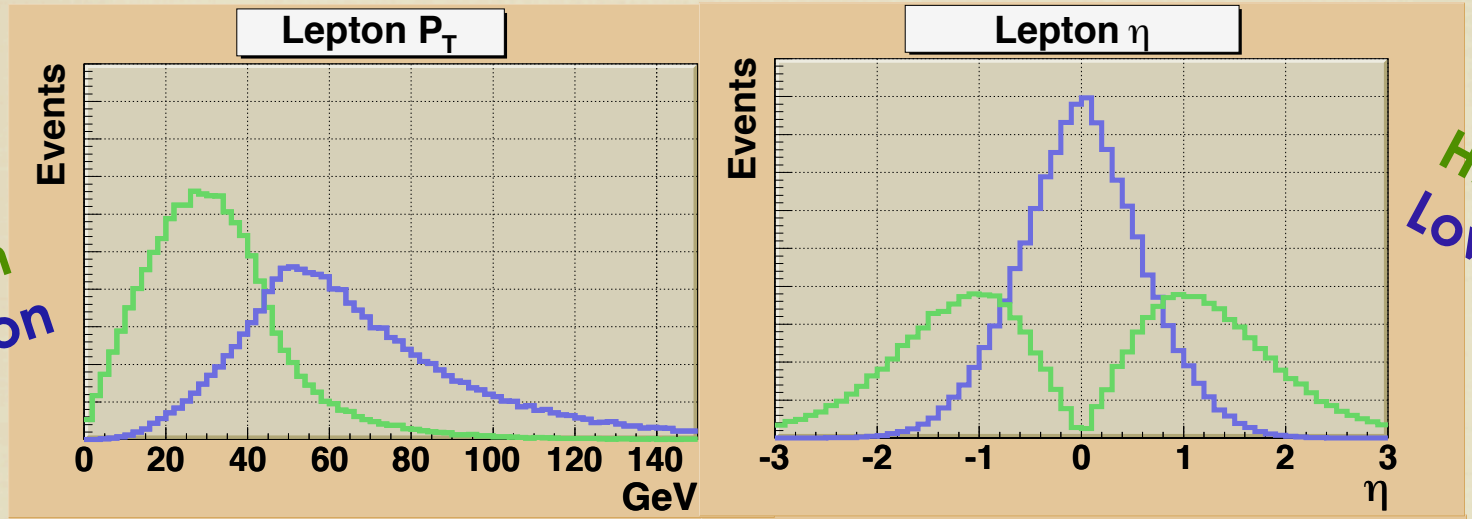


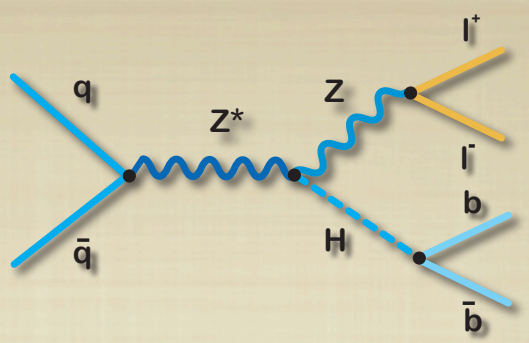
Low p_T lepton
High p_T lepton

High η lepton
Low η lepton

Low p_T b-quark
High p_T b-quark

High η b-quark
Low η b-quark

What to expect ?



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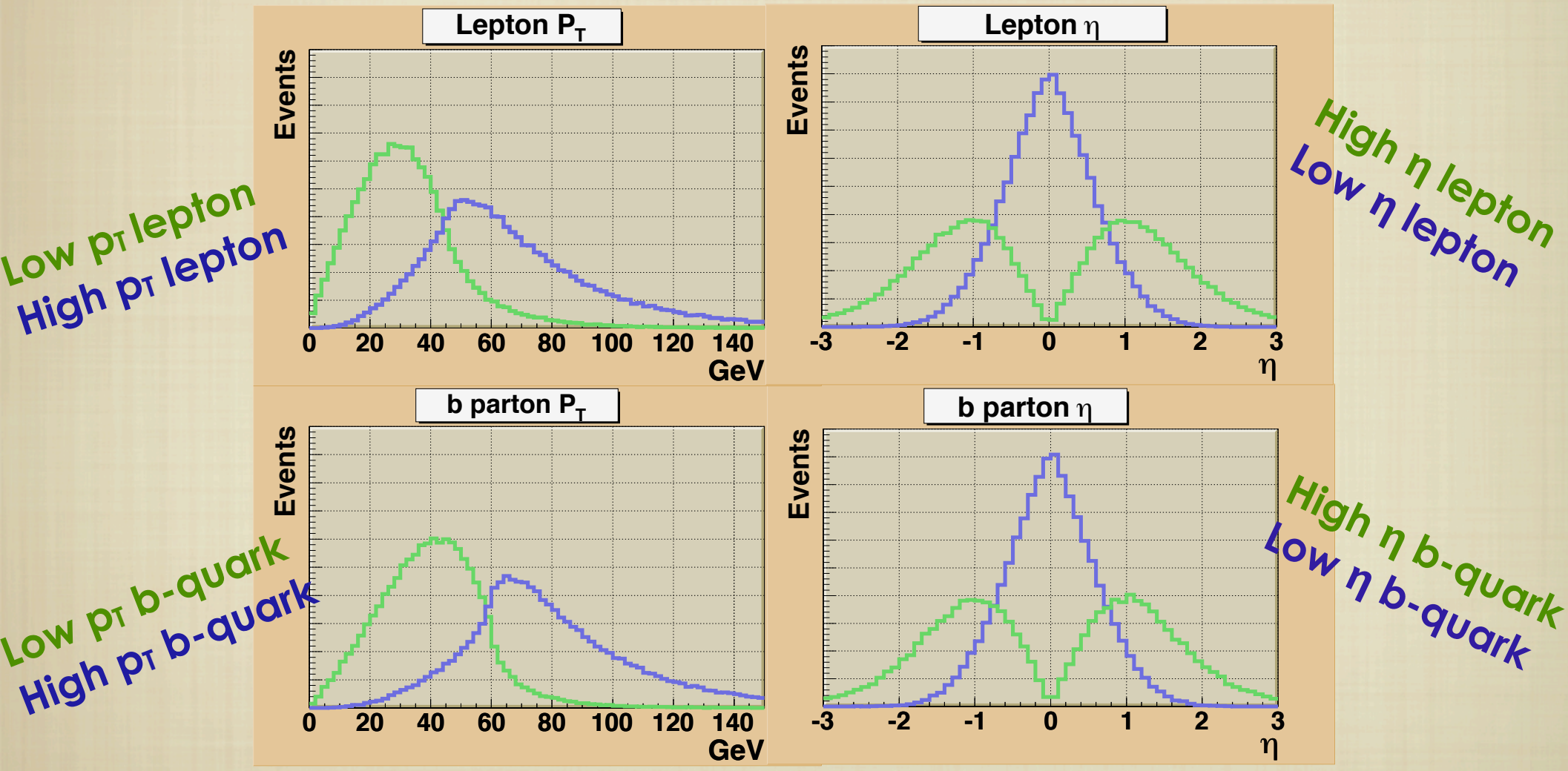


Low p_T lepton
High p_T lepton

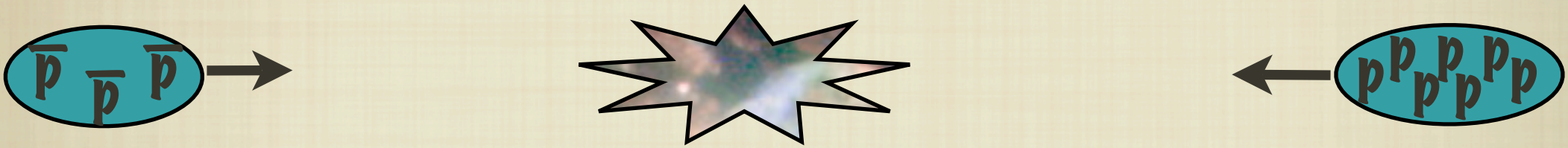
High η lepton
Low η lepton

Low p_T b-quark
High p_T b-quark

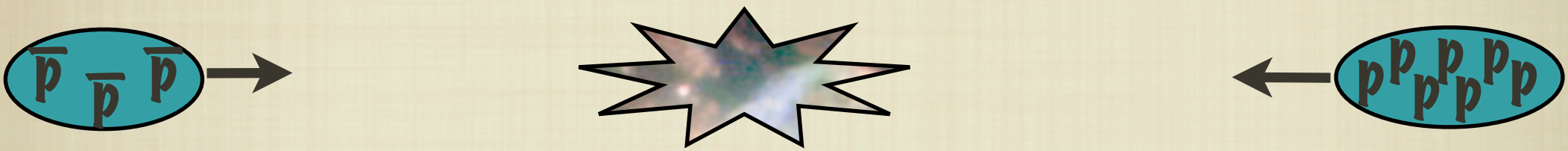
High η b-quark
Low η b-quark

Use these distributions as a guide to determine selection


$\bar{p}$ $\bar{p}$ $\bar{p}$
p p p p p p


$\bar{p}$ $\bar{p}$ $\bar{p}$
p p p p p p

Available Tools : CDF



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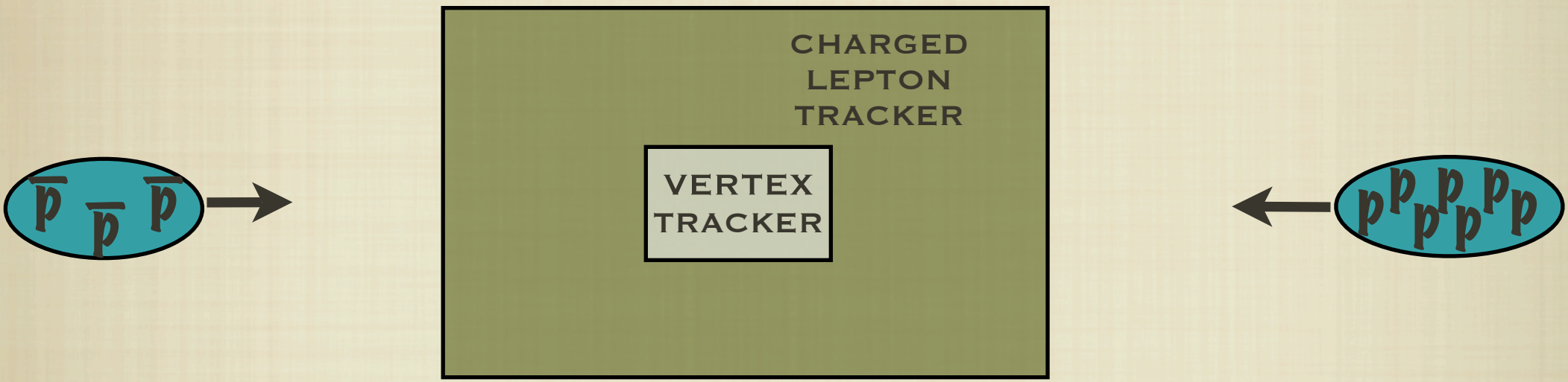

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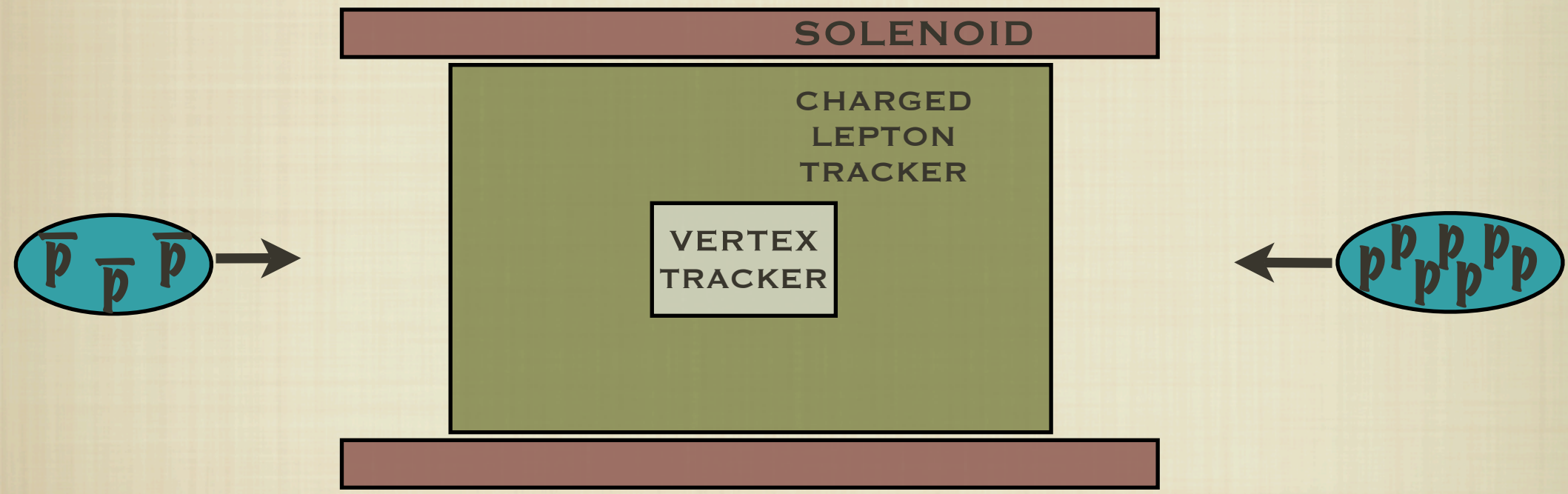

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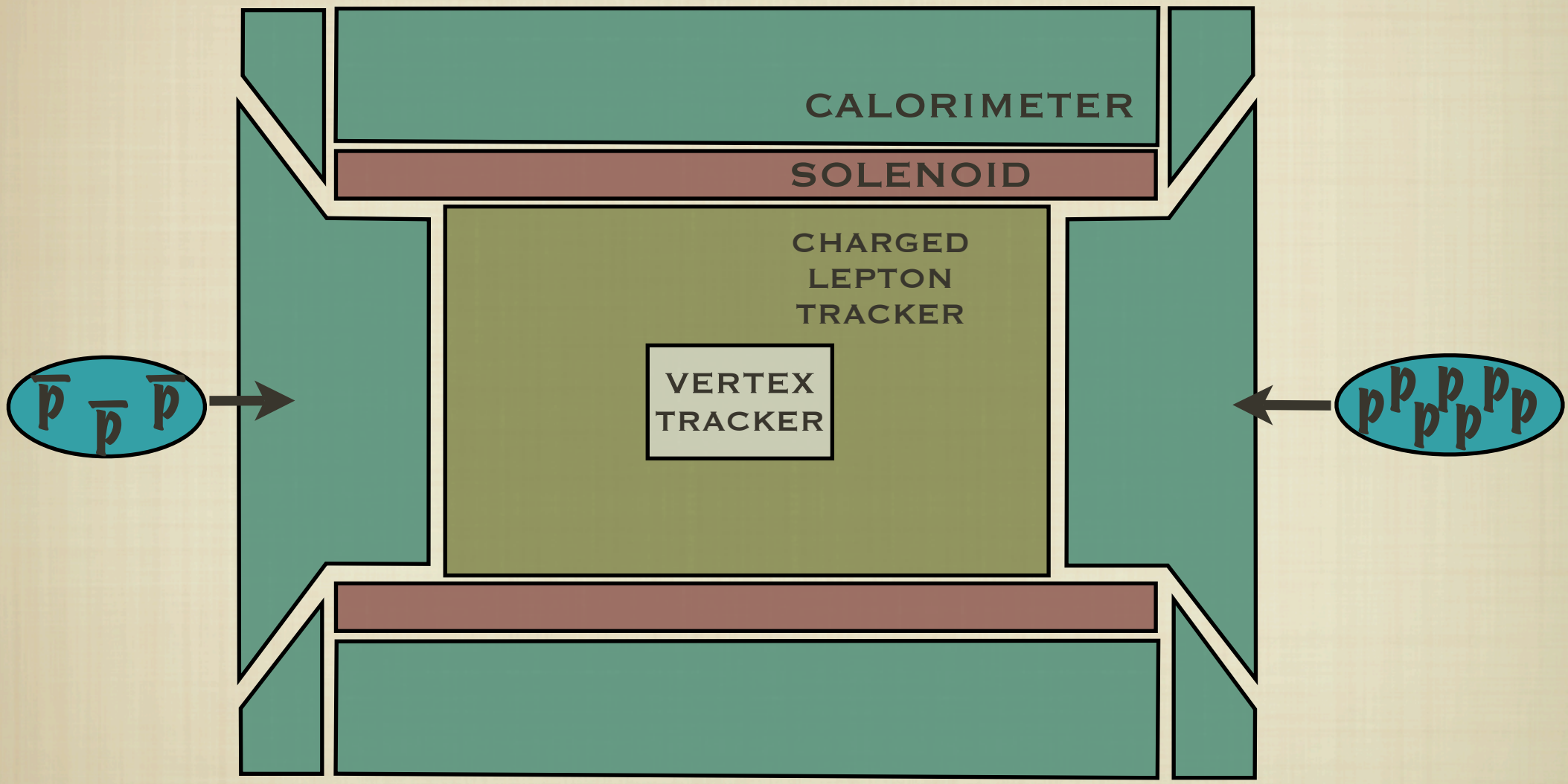
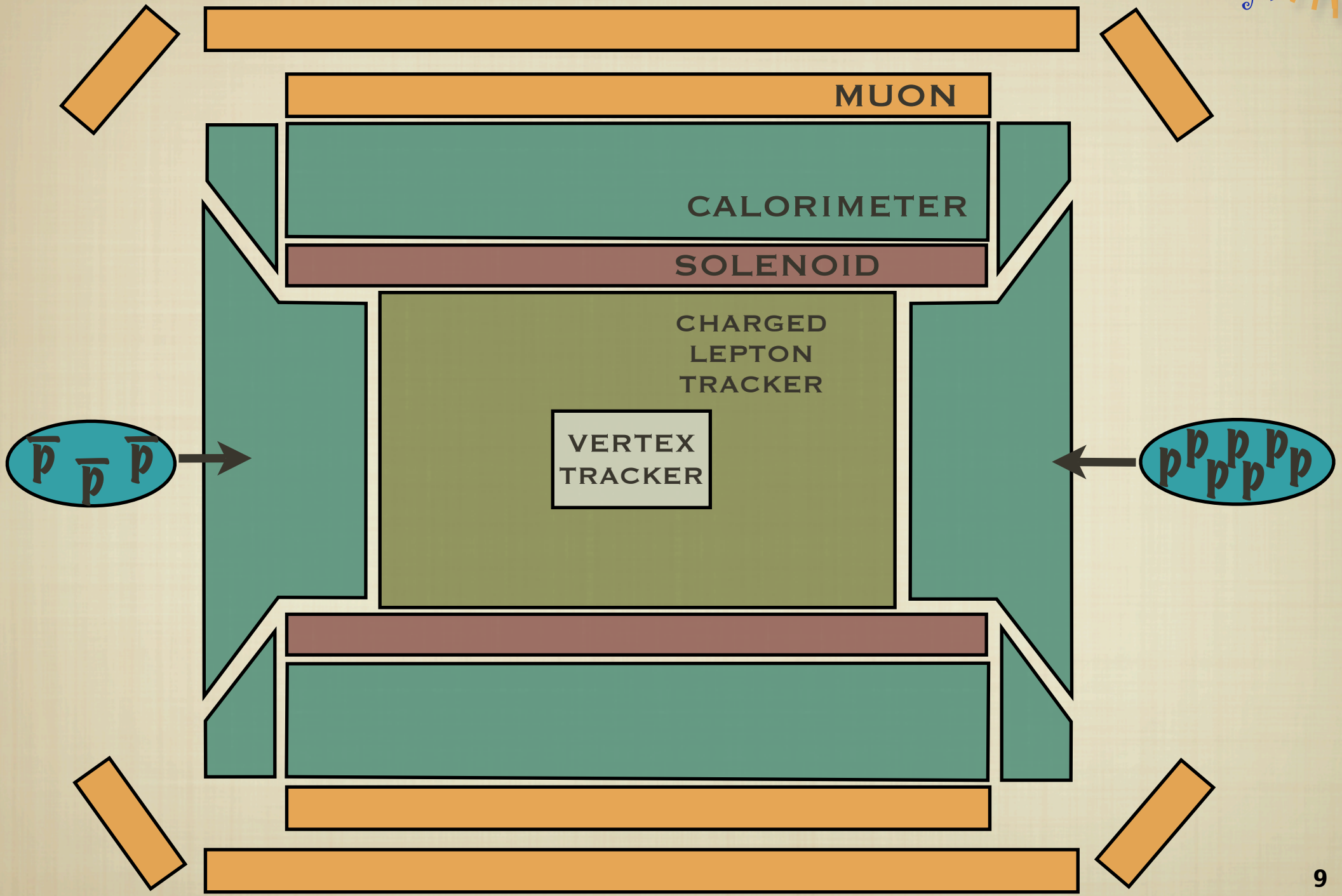
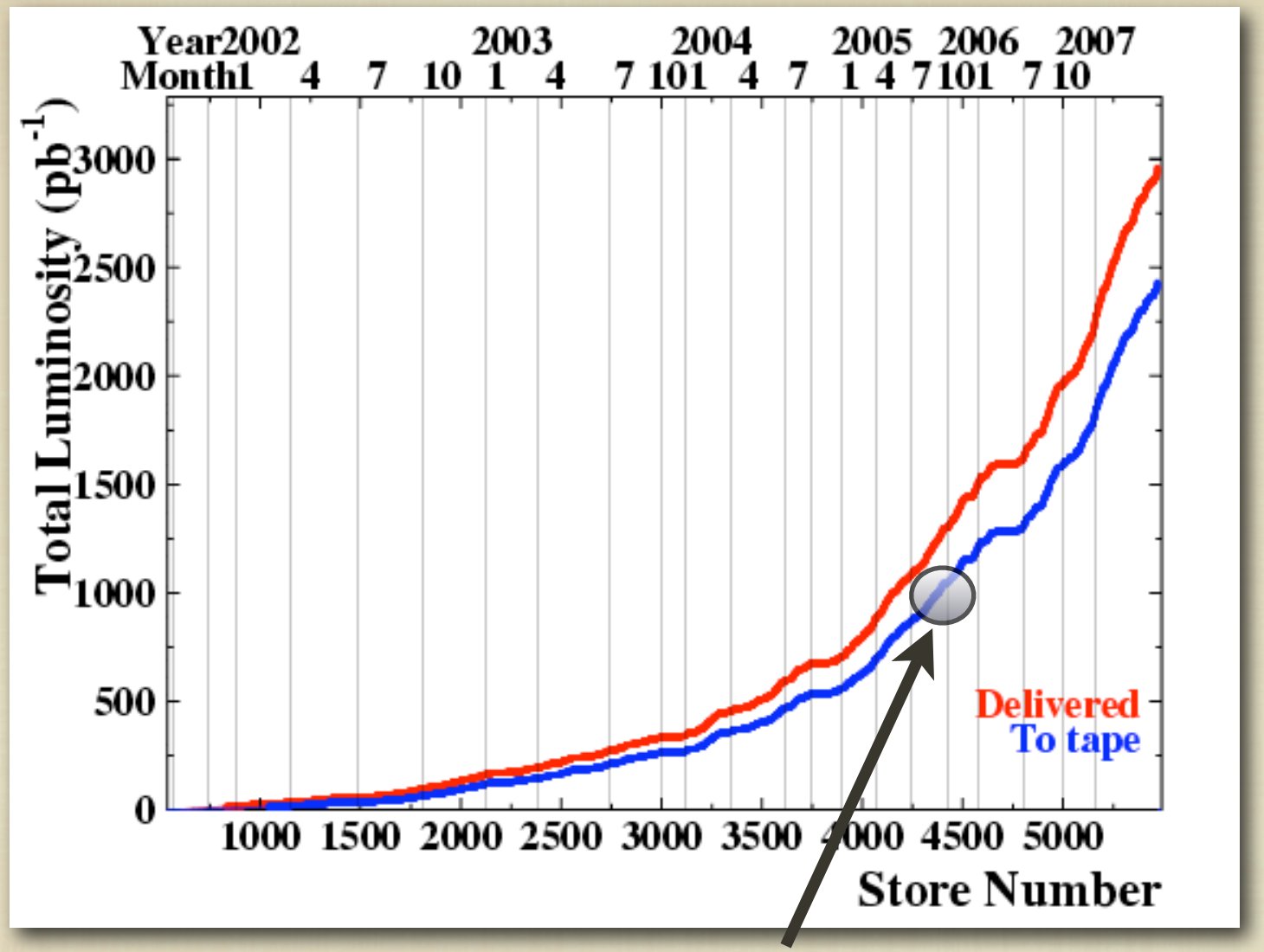


Available Tools : CDF



Accumulated CDF data



- Analysis today presents 1 fb^{-1}
- Current data on tape is 2.5 fb^{-1}

BEFORE ANY EVENT SELECTION

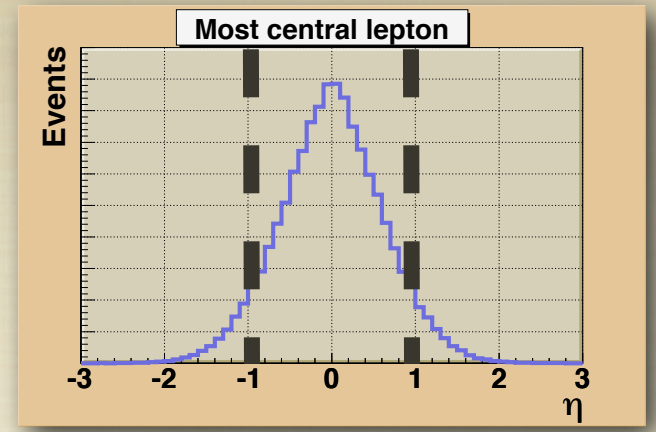
Higgs events : Everything else

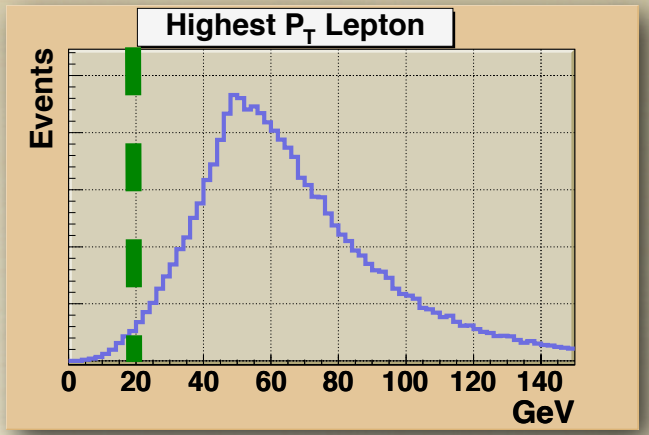
5 : 100,000,000,000,000

in 1 fb^{-1} data

Maximizing ZH Acceptance

Online selection first lepton





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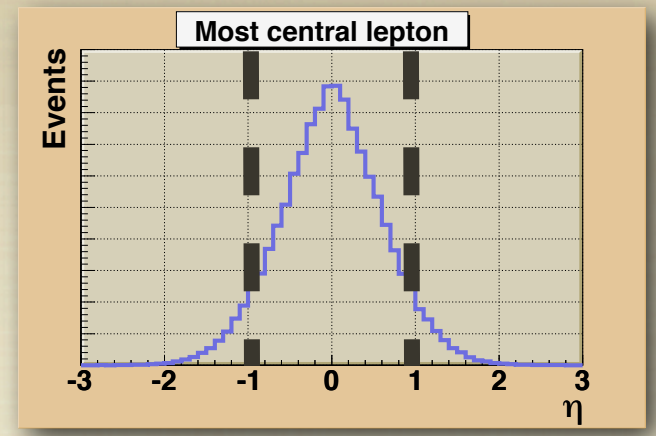
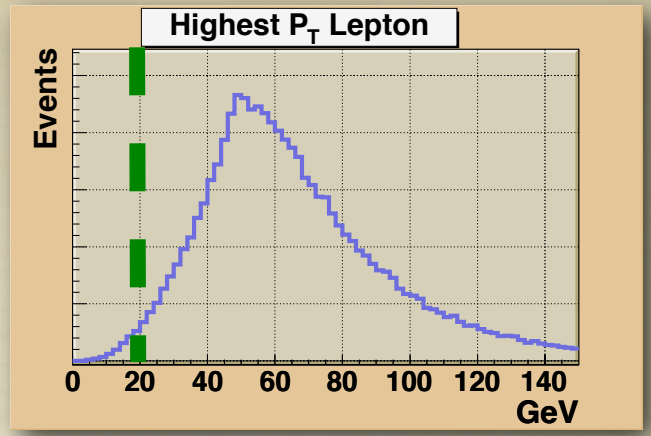
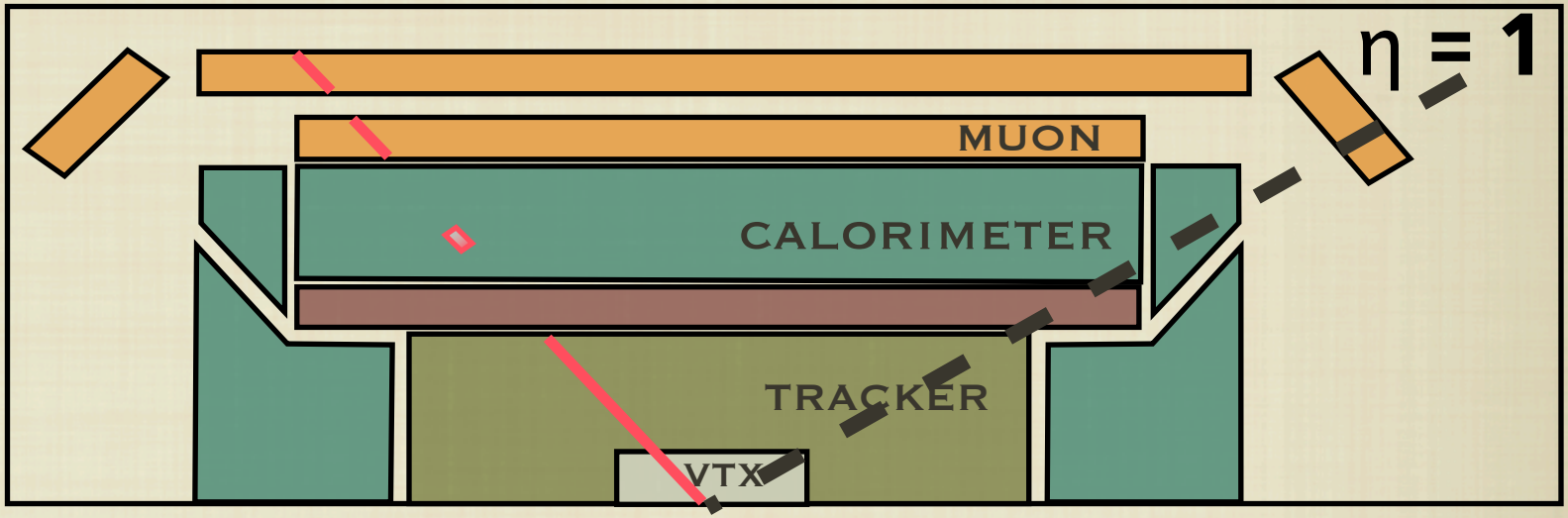




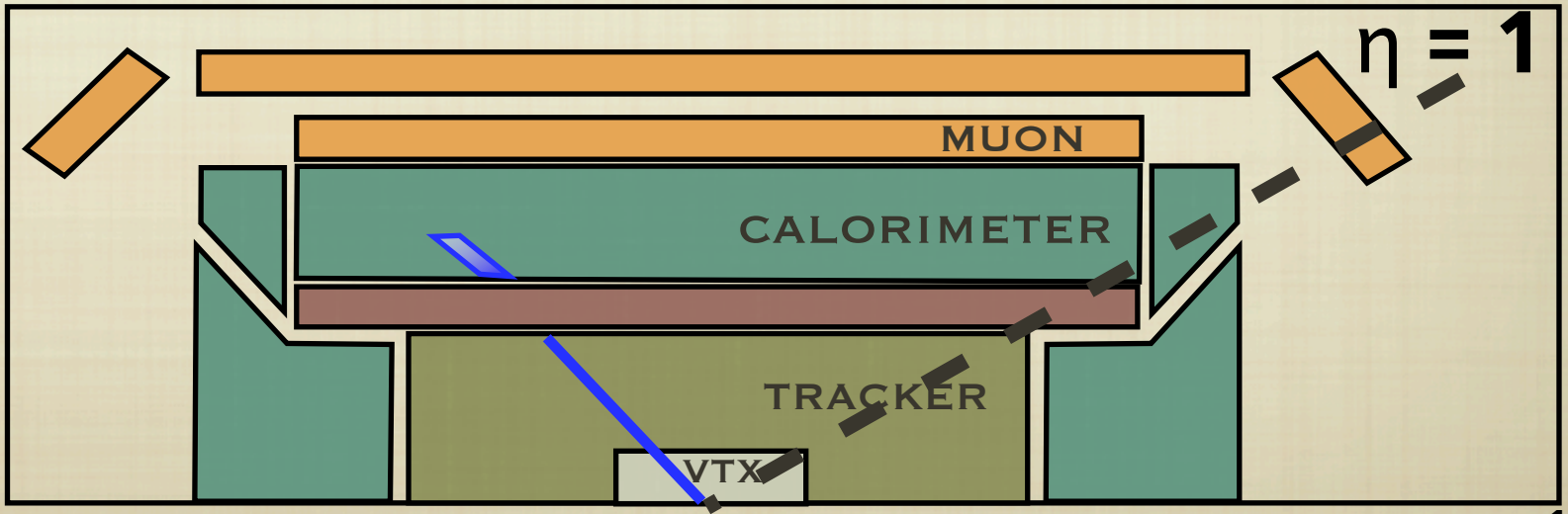
MUONS

- Track p_T > 18 GeV
- $|\eta|$ < 1
- Muon segment
- Isolated
- Quality cuts



ELECTRONS

- EM E_T > 18 GeV
- $|\eta|$ < 1
- Track p_T > 8
- HAD E_T small
- Isolated
- Quality cuts



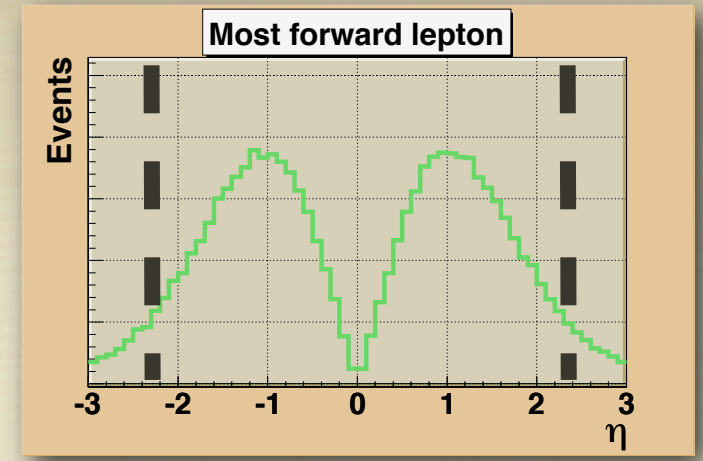
SELECTED ONE
LEPTON ON-LINE

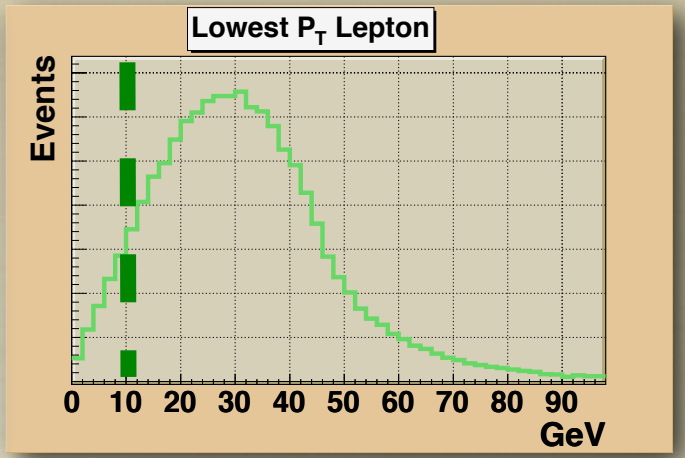
Higgs events : Everything else

2 : 100,000,000

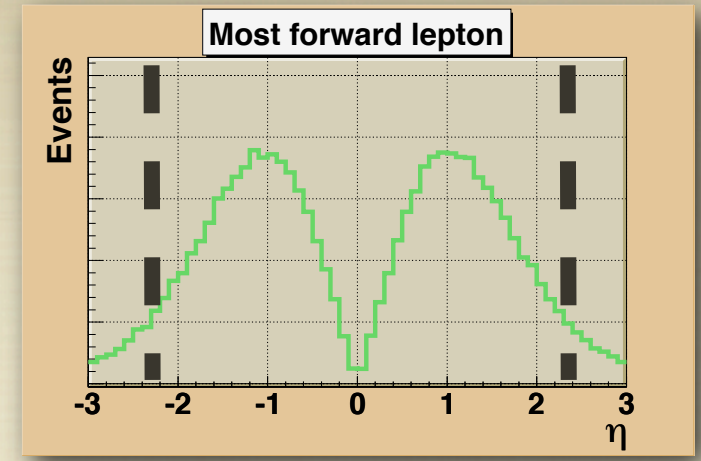
in 1 fb^{-1} data

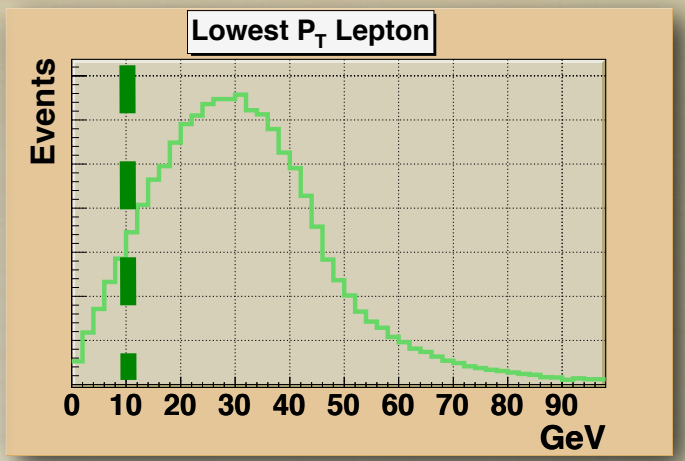
Loose selection second lepton





Loose selection second lepton





MUONS

- Track p_T > 10 GeV
- |η| < 1.5
- Minim. ionizing
- Isolated

ELECTRONS

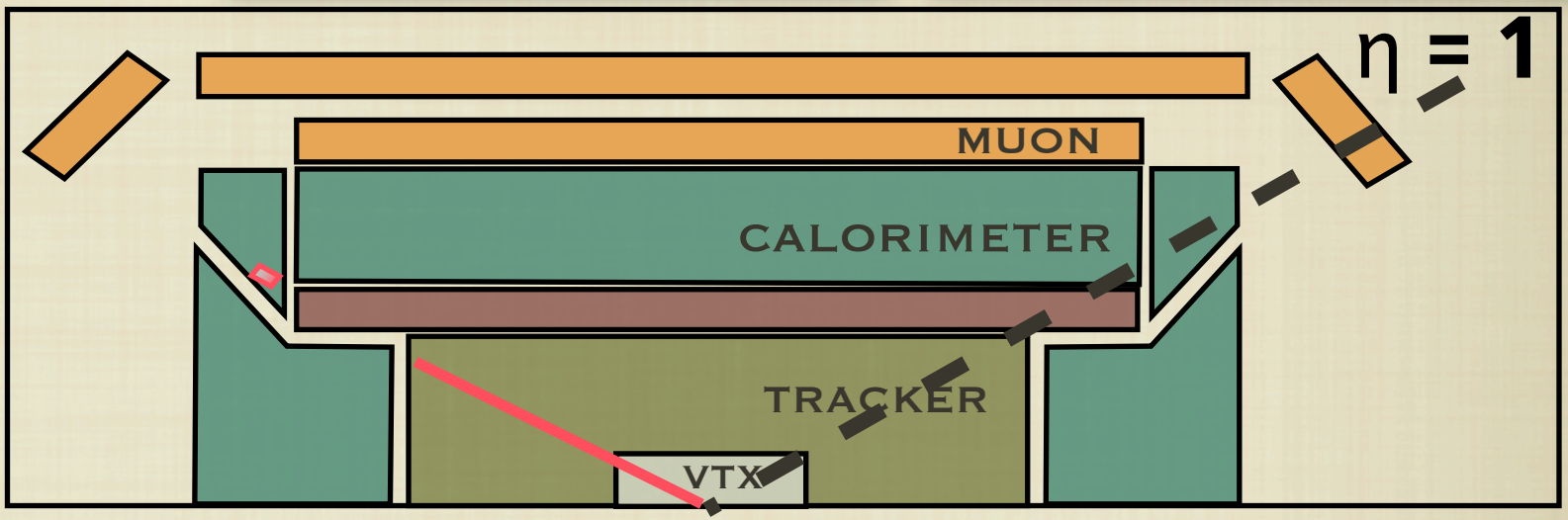
- |η| < 2.4
- HAD E_T small
- Isolated

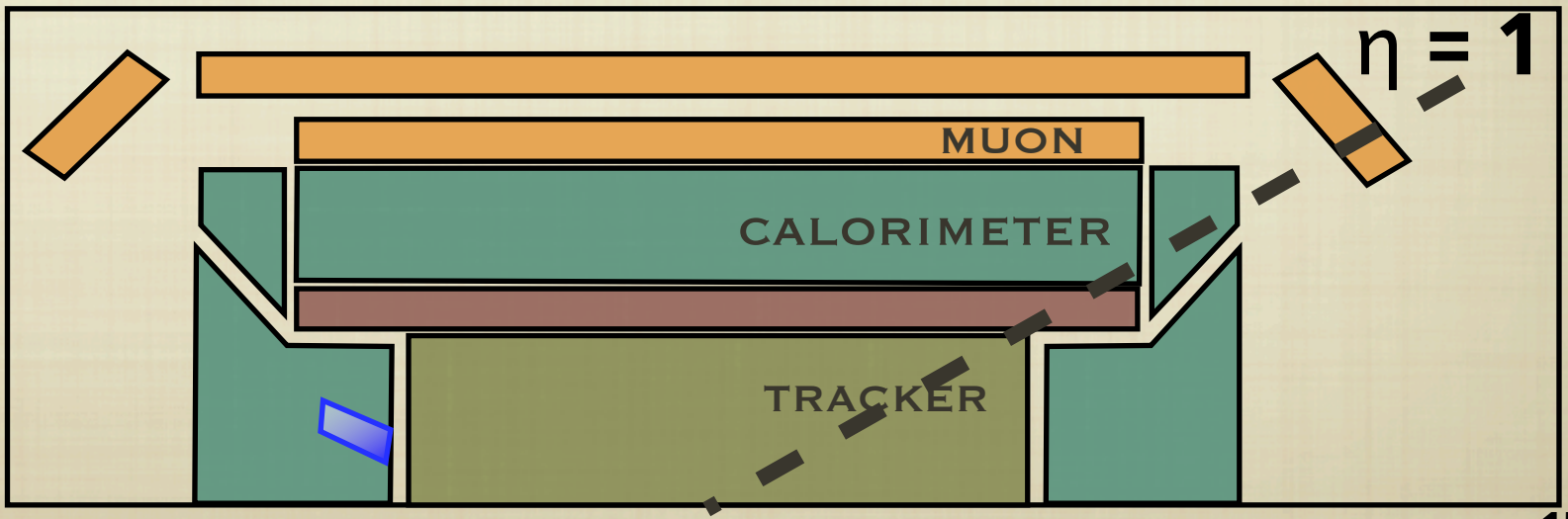
Central

- EM E_T > 10 GeV
- Track p_T > 5 GeV

Forward

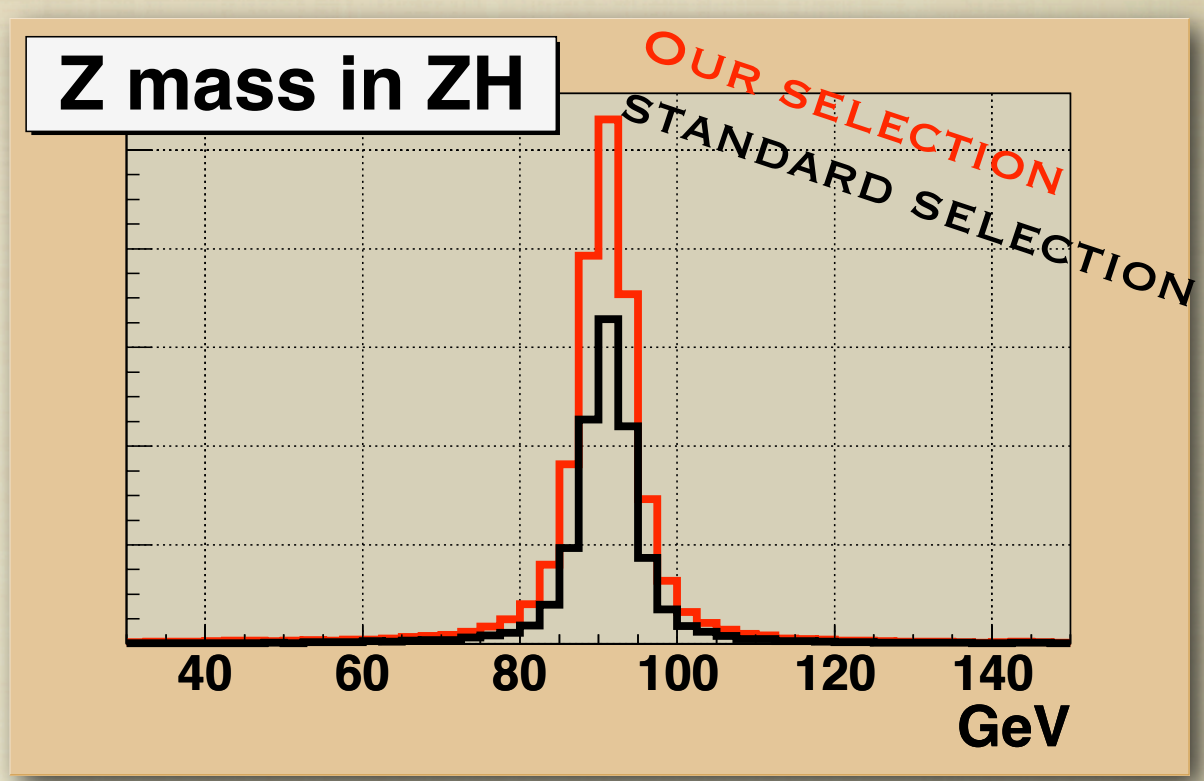
- EM E_T > 20 GeV





Improved Higgs acceptance

- Efforts pay off
- 70% more signal acceptance than cuts used in top dilepton group
- 0.9 → 1.5 ZH events after Z selection



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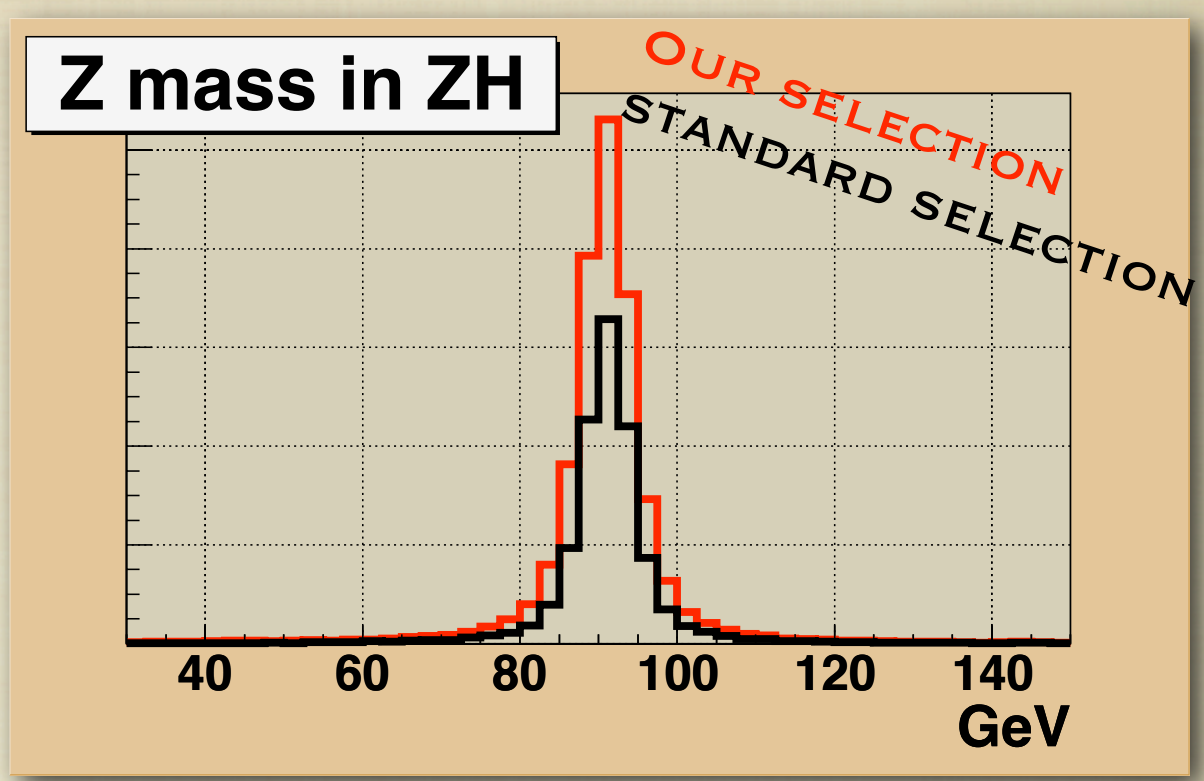


- What about background from "fake" leptons ?
  - Rate to for leptons to be mis-reconstructed evaluated in jet-enhanced data & same-charge dilepton events
  - "Fake Z bosons" < 2% of Z boson candidate sample !

SELECTED Z CANDIDATES

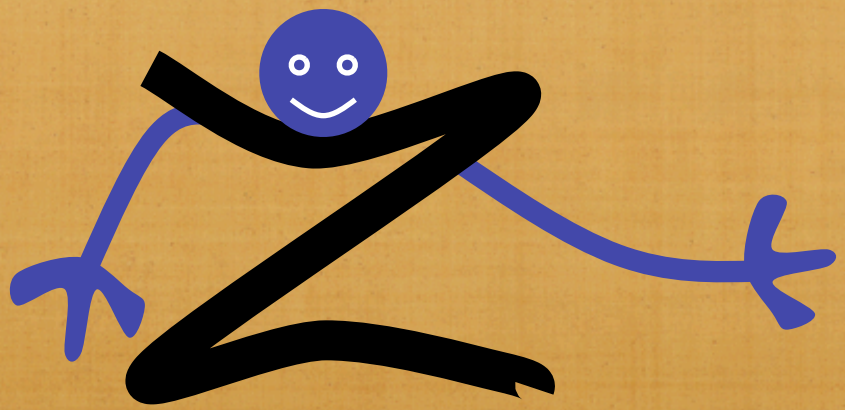
Higgs events : Everything else

1.5 : 150,000

in 1 fb^{-1} data

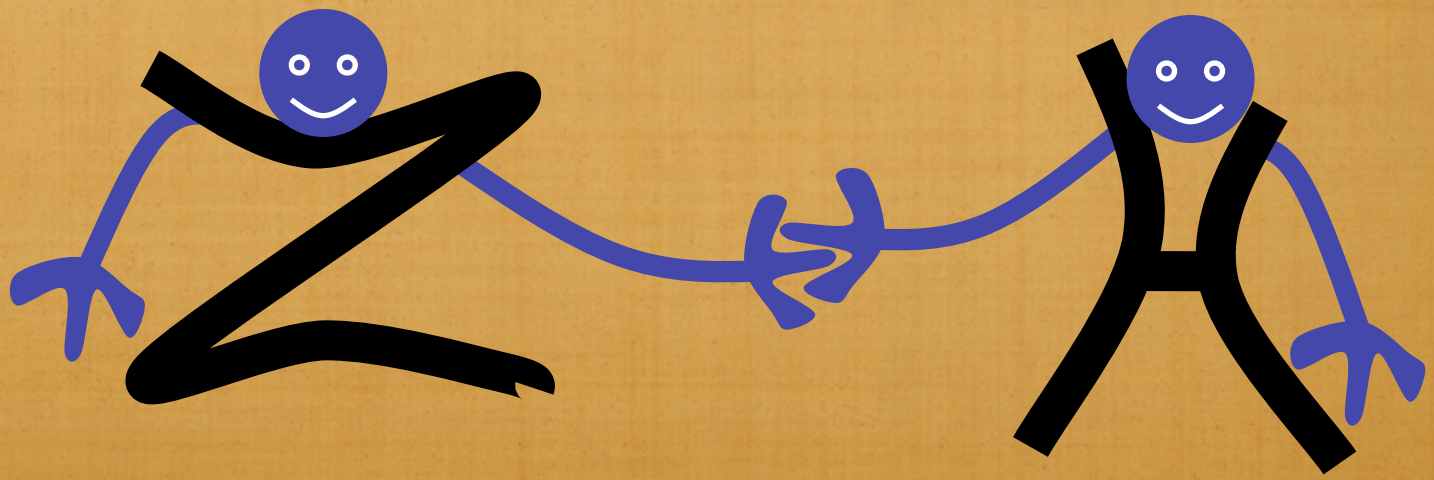
Now we've got our Z

Let's search for any important associates

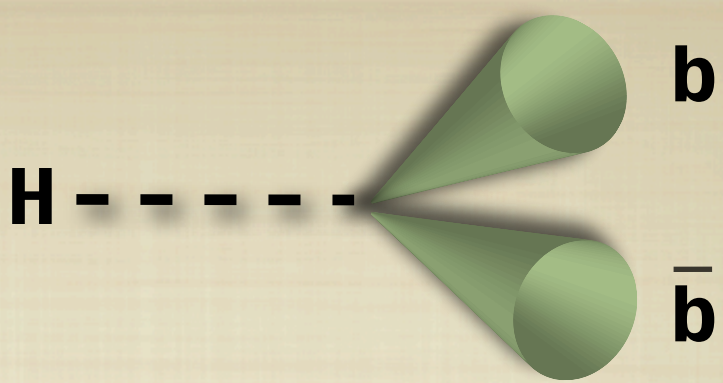


Now we've got our Z

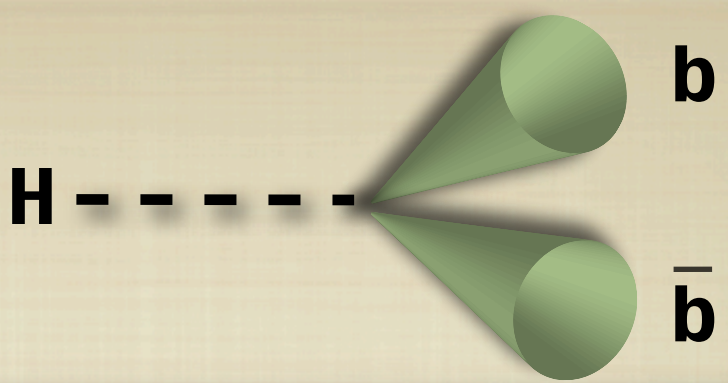
Let's search for any important associates

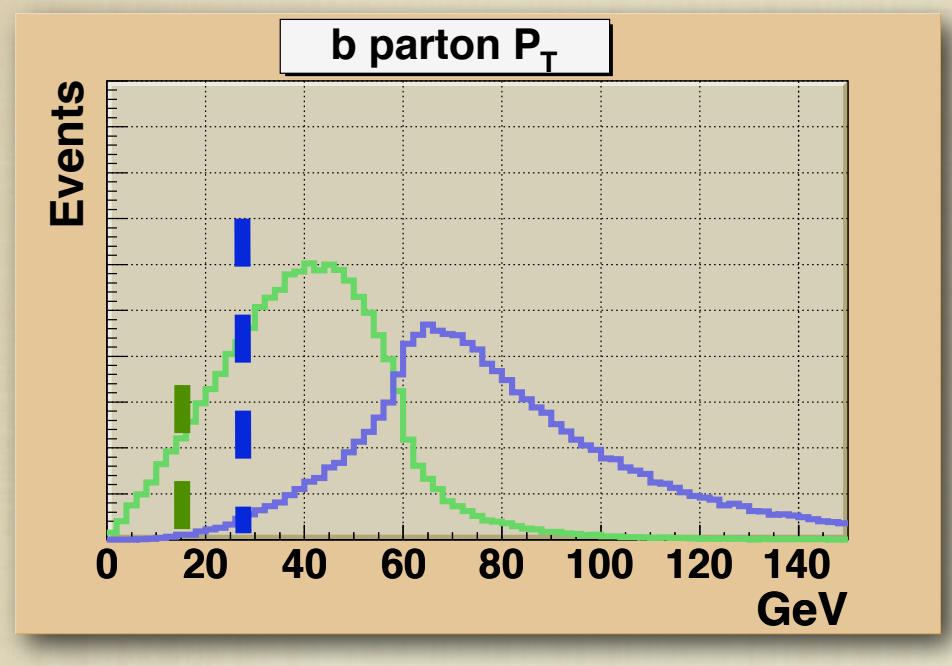


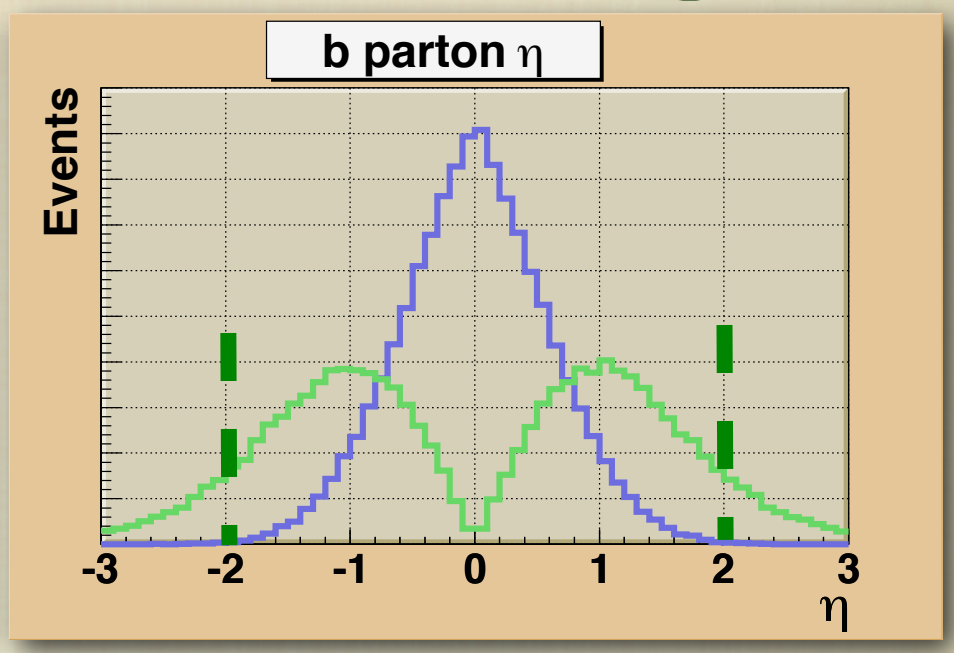
Selection of Jets



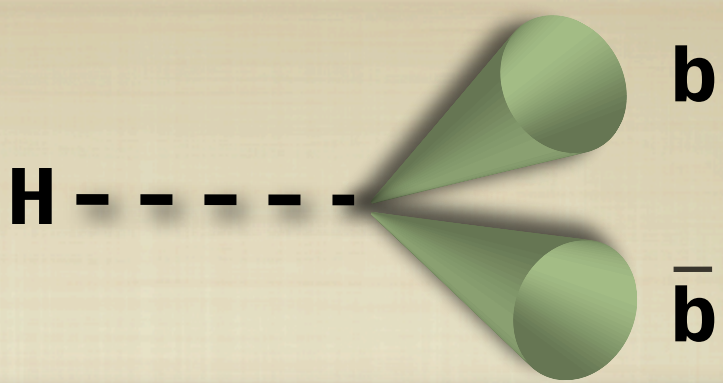
Selection of Jets

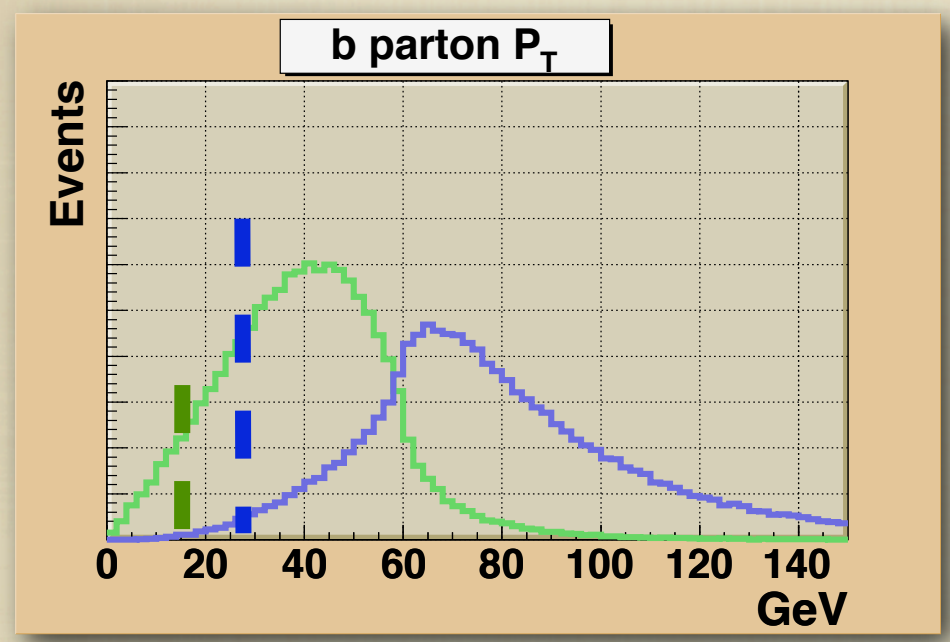


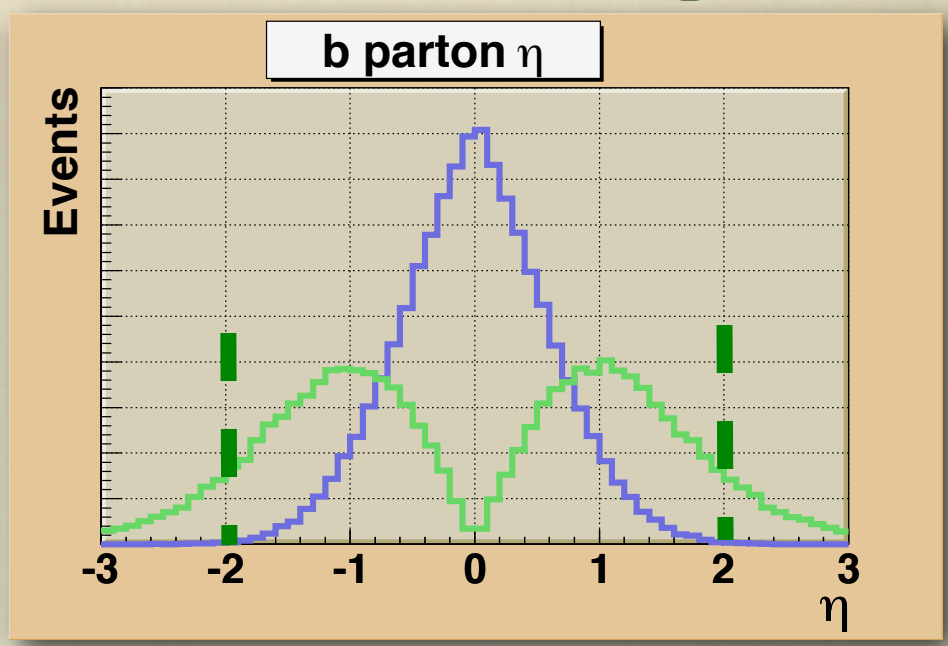




Selection of Jets





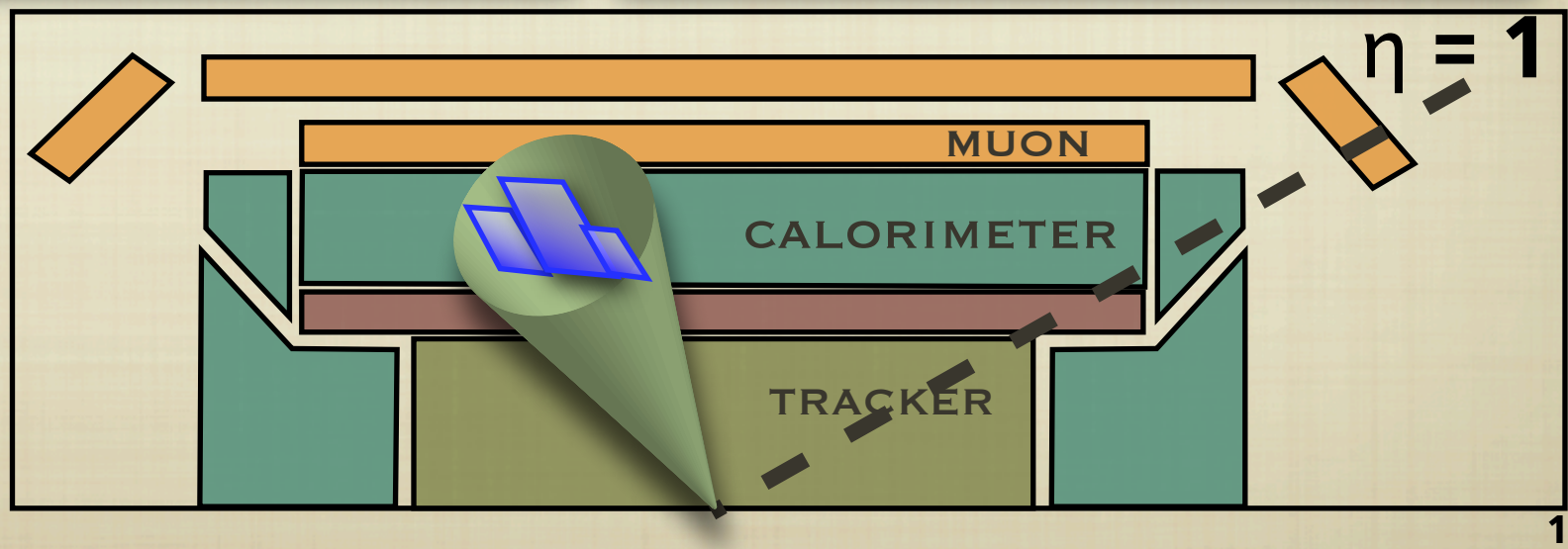


1st jet

- E_T > 25 GeV
- |η| < 2.0

≥2nd jet

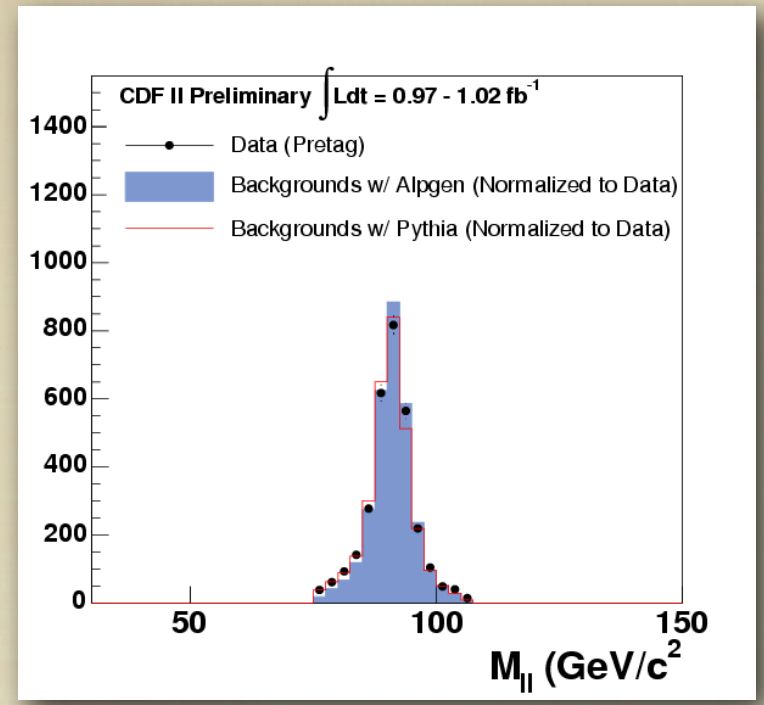
- E_T > 15 GeV
- |η| < 2.0

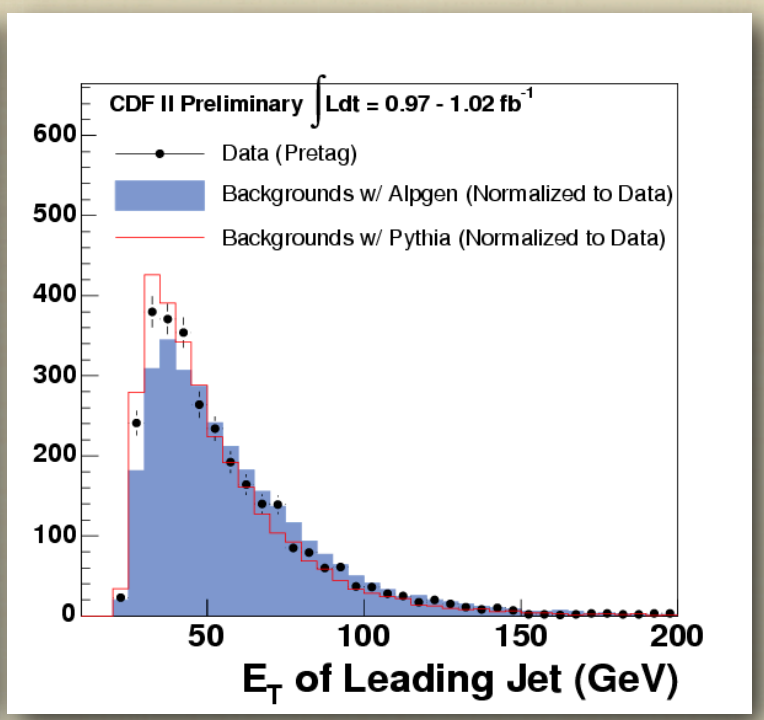


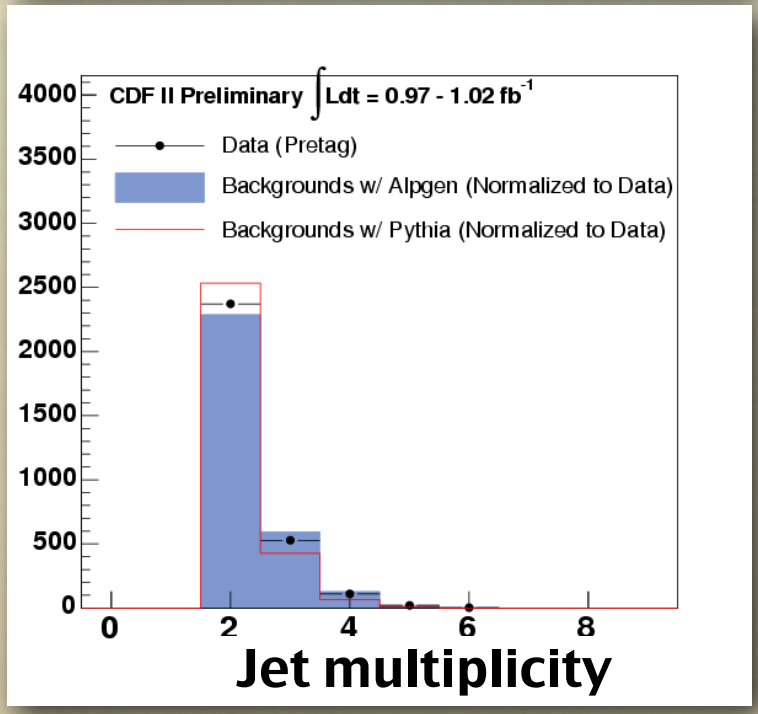
Modeling of Z + ≥ 2 jets

- Compare data to background model
  - 95% Z+jets
    - Model with Alpgen + Herwig
      - Better at modeling harder extra jet activity
    - Compare to Pythia
      - Well-tuned to our data : "Tune A", "Z p_T tune"
  - 4% comes from
    - Fakes (for instance, W+jets with a jet misidentified as a lepton)
      - Model from data
    - ZW, ZZ, tt
      - Model from Pythia

Data / Model Comparisons for Z + ≥2 jets







Two models span data well

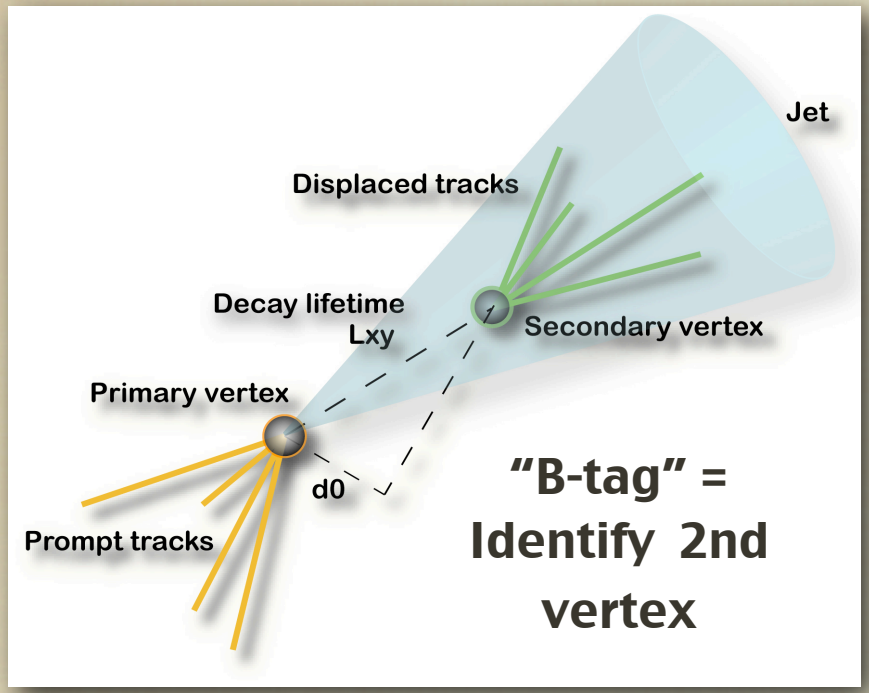
SELECTED Z + JETS

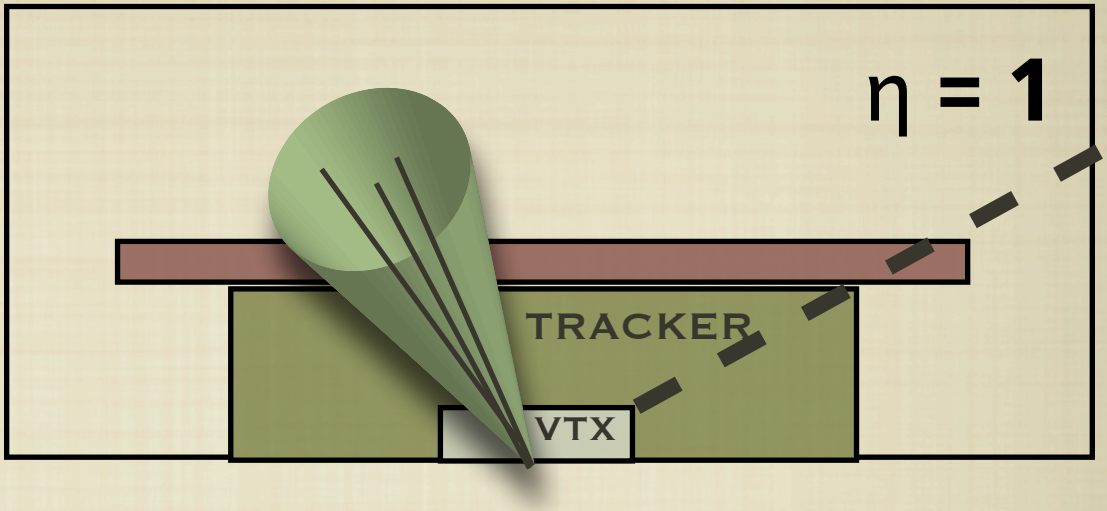
Higgs events : Everything else

1 : 3,000

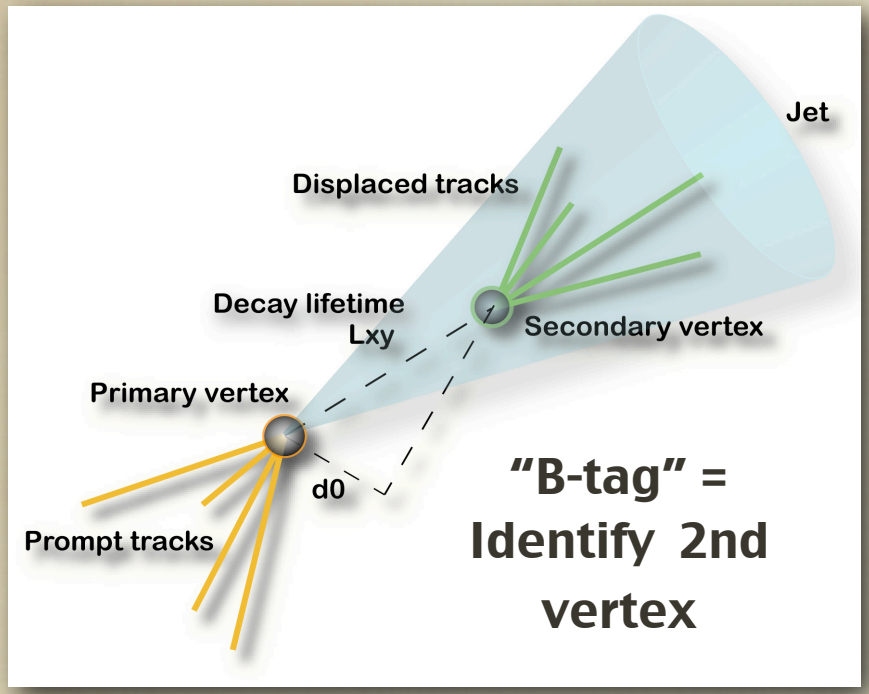
in 1 fb^{-1} data

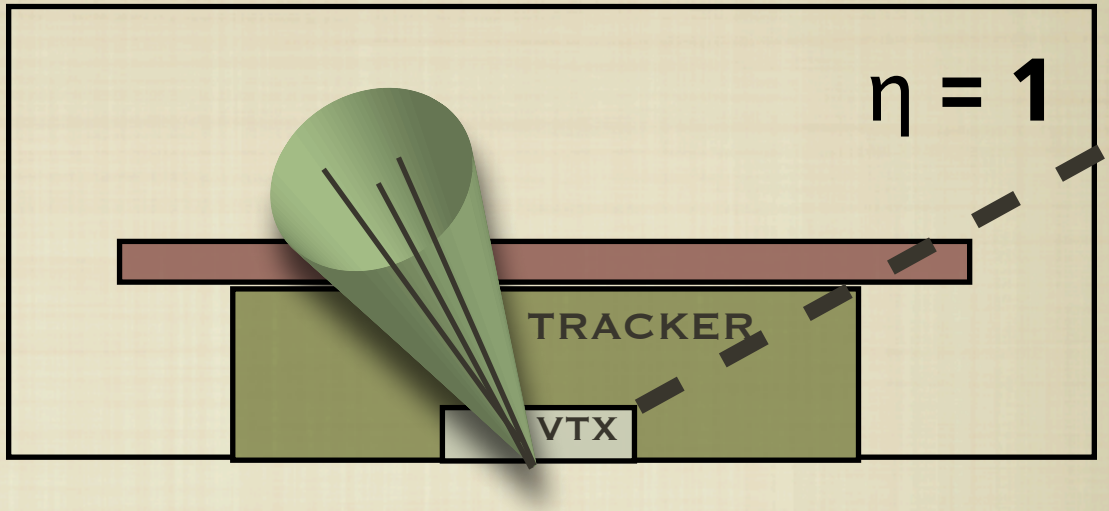
B-tagging our jets

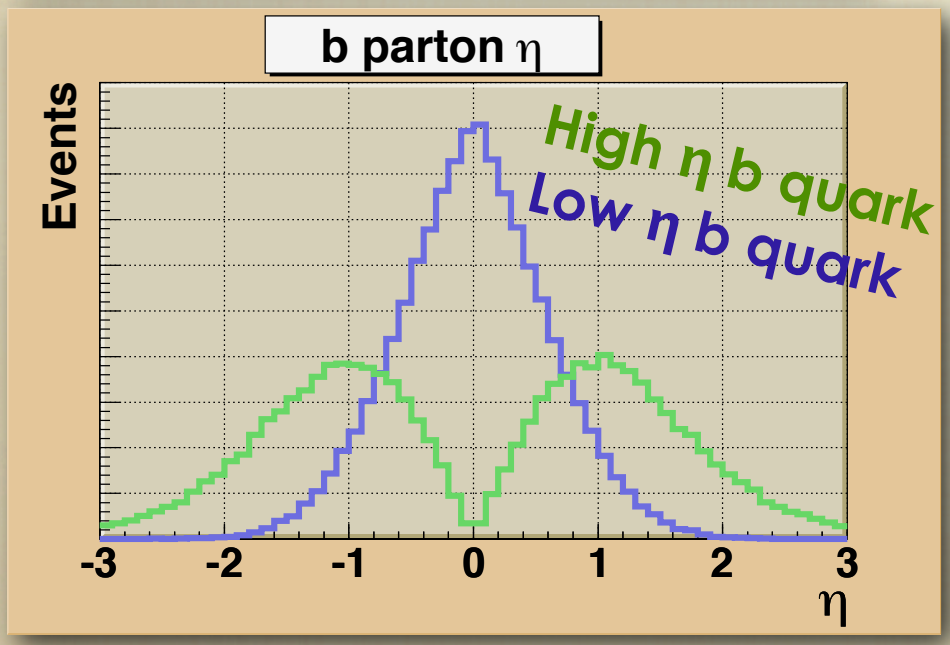


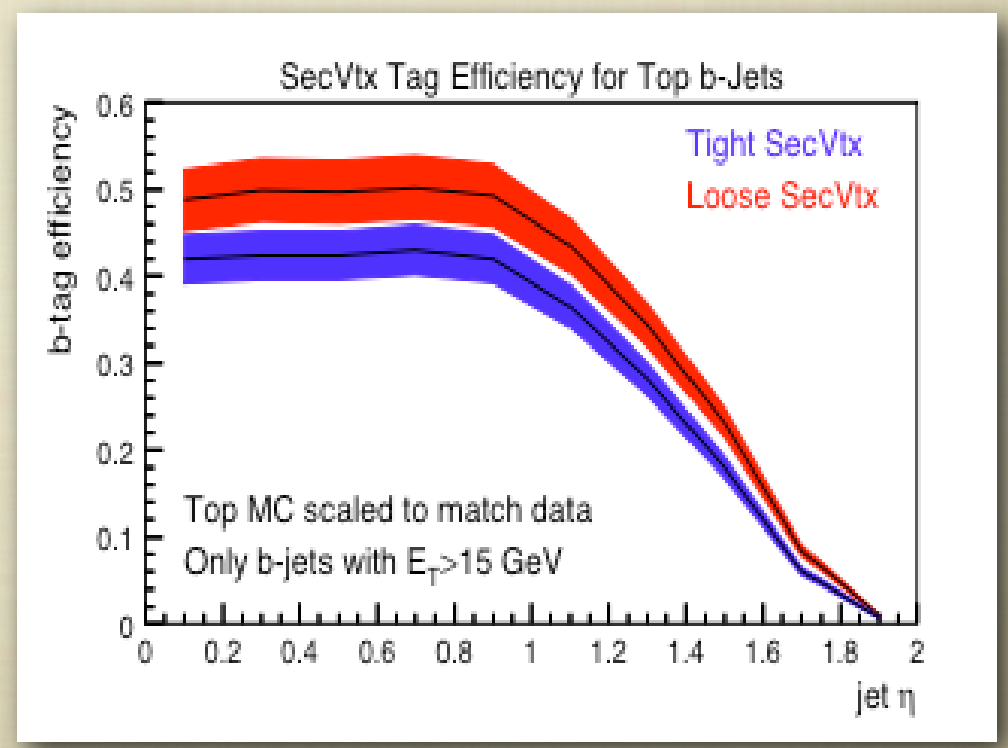


B-tagging our jets

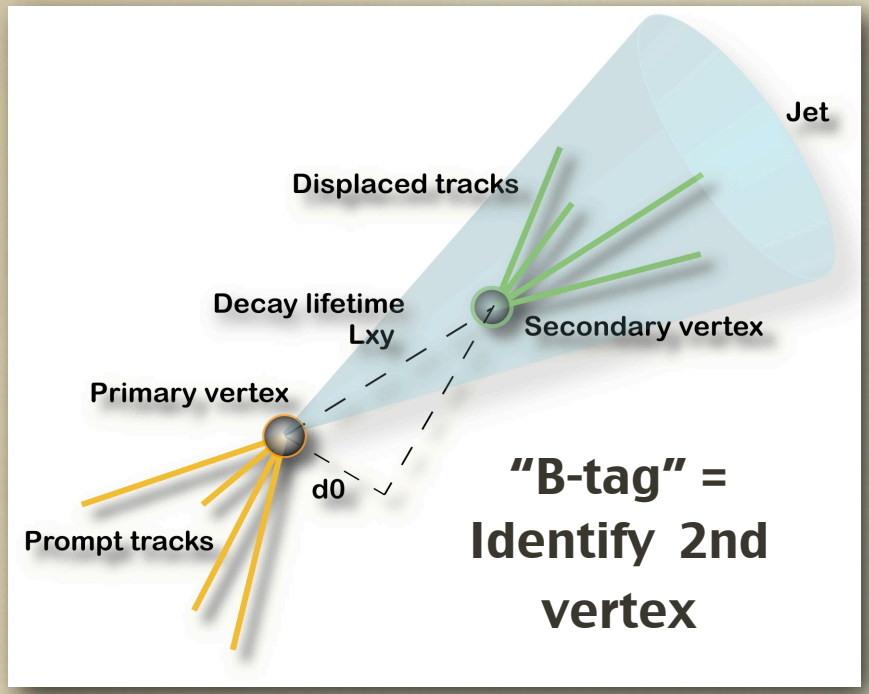


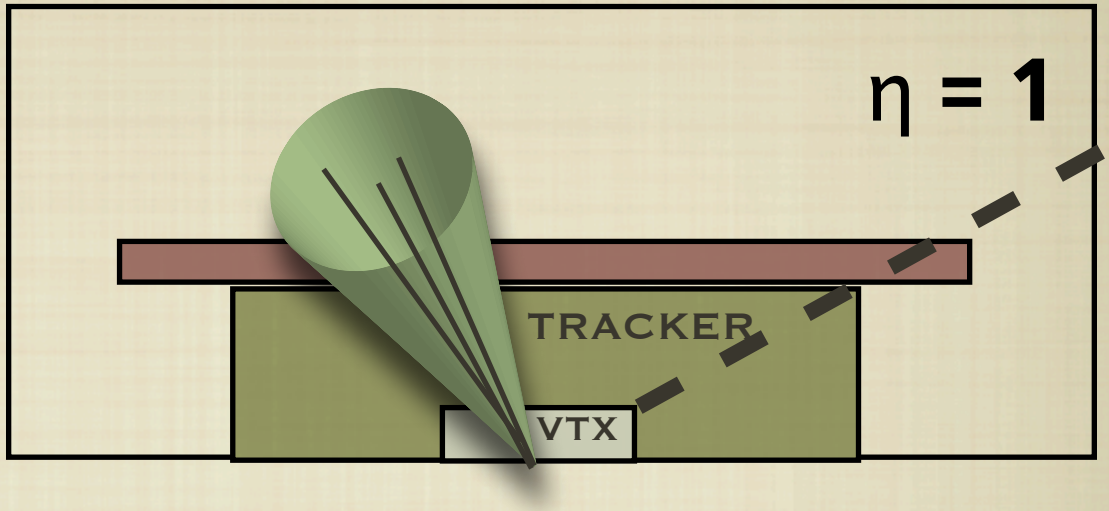


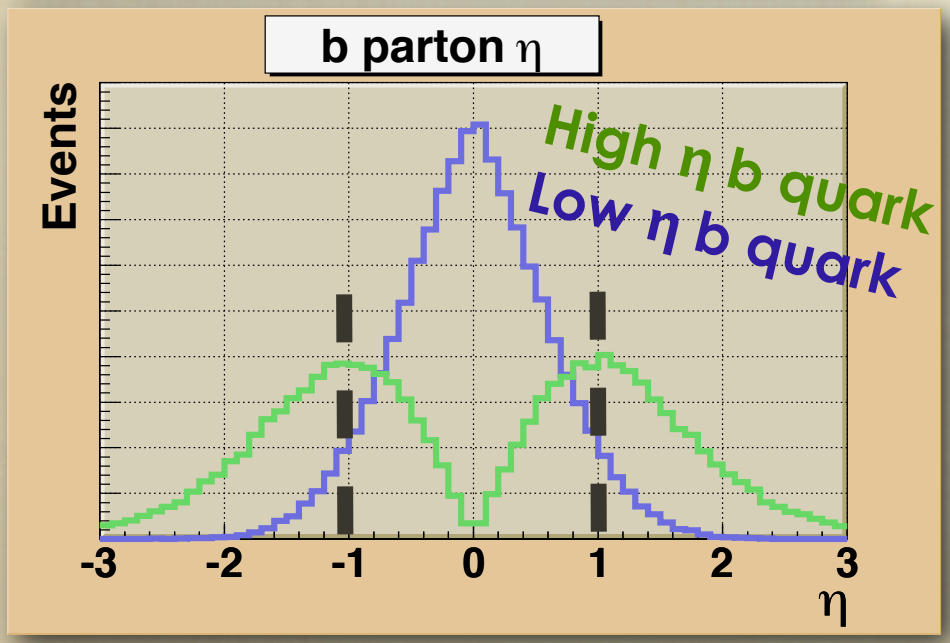


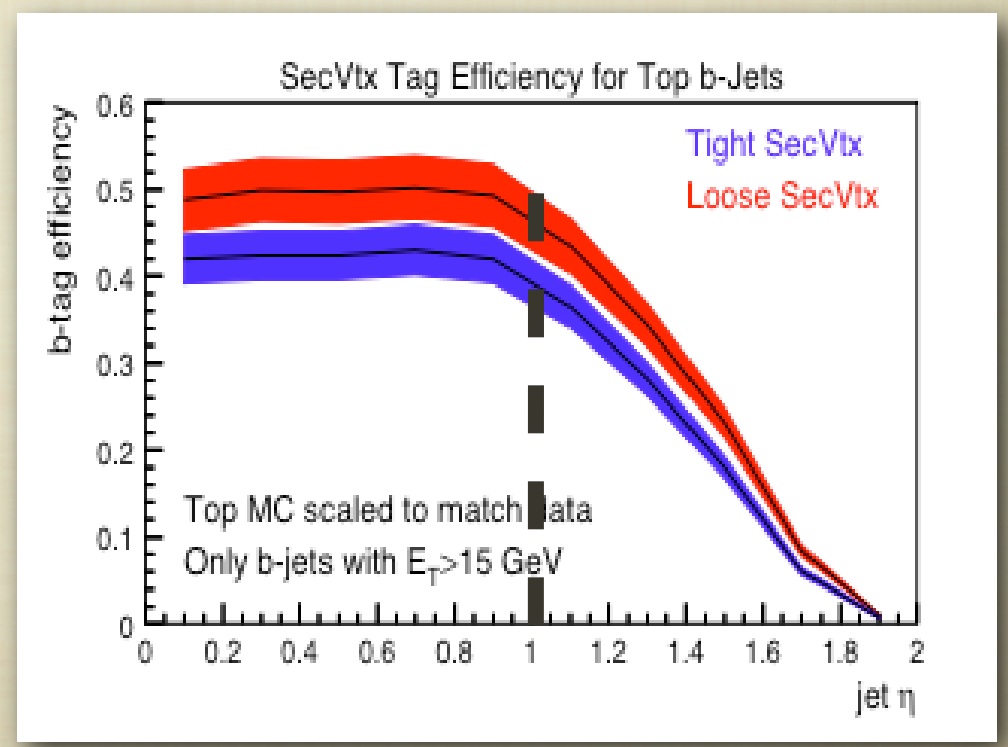


B-tagging our jets

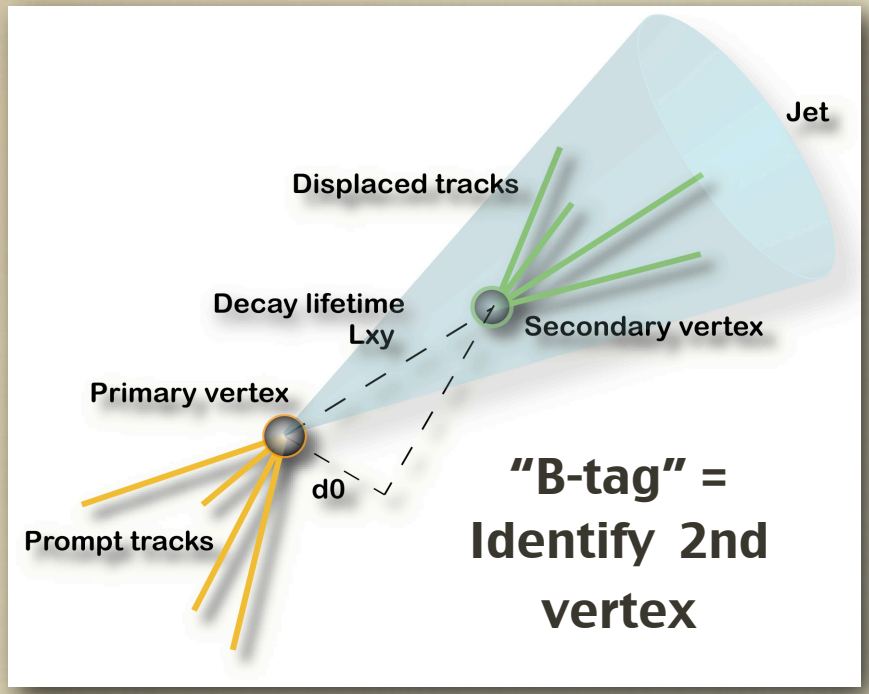


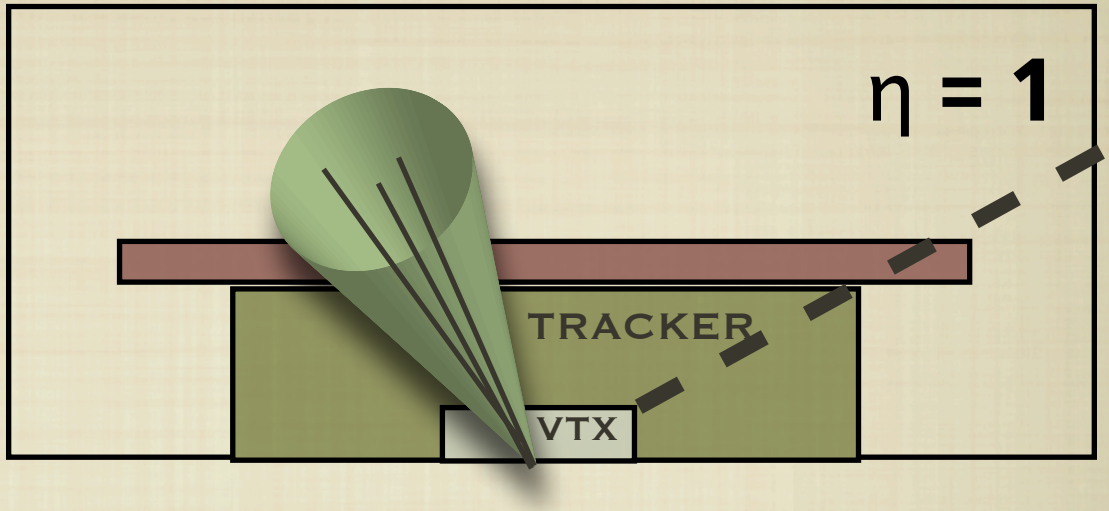


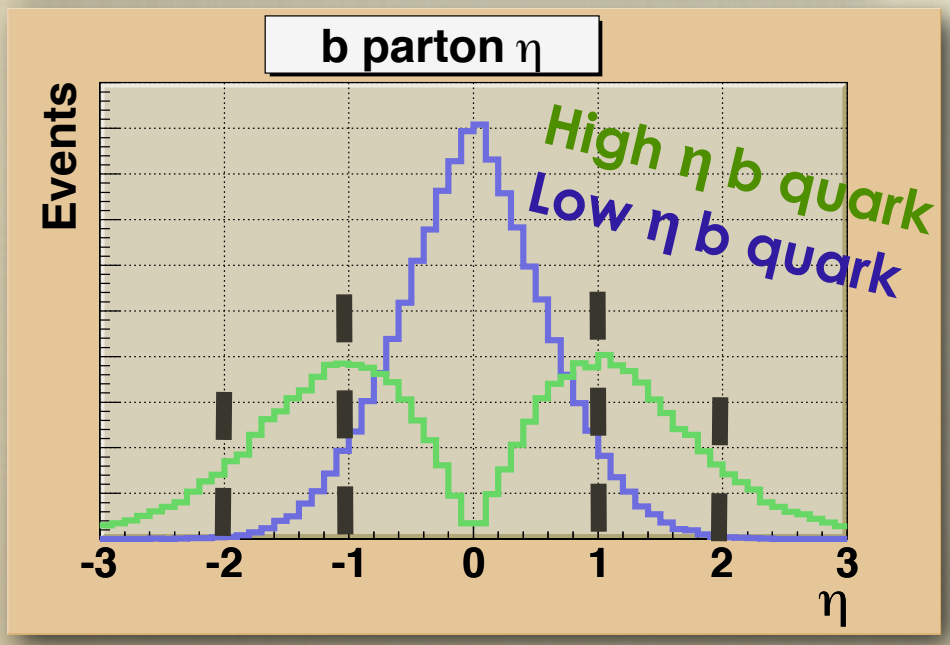


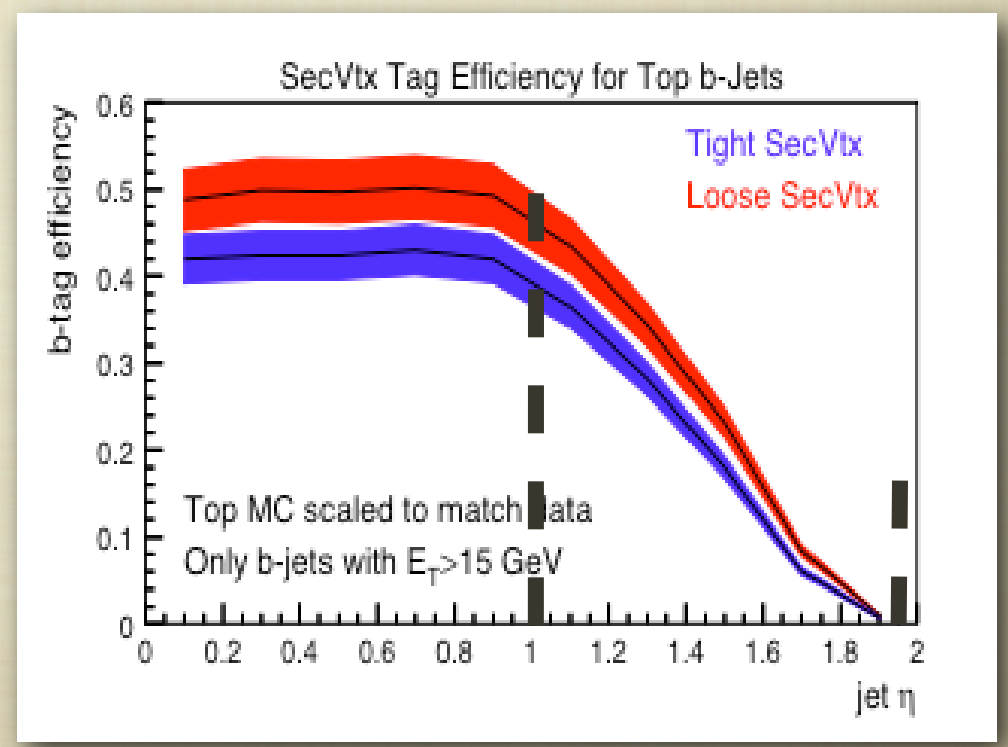


B-tagging our jets









SELECTED Z + JETS
+ B-TAG

Higgs events : Everything else

0.7 : 110

in 1 fb^{-1} data

Smarter b-tagging

- Split events into exclusive categories
  - Two loose b-tags
    - Each 50% efficient, 1.5% fake rate
    - Subsample with better signal to background
  - One tight b-tag
    - 40% efficient, 0.5% fake rate
  - Separating improves sensitivity to ZH signal

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Events w/one tag 1 fb^{-1}	
Signal	0.44
Z+bb	35
Z+fake B	32
Total background	102
Data	100

Events w/two tags 1 fb^{-1}	
Signal	0.23
Z+bb	6.3
Z+fake B	1.0
Total background	12.4
Data	11

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Signal	0.44
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Z+fake B	32
Total background	102
Data	100

1/3

Events w/two tags 1 fb^{-1}	
Signal	0.23
Z+bb	6.3
Z+fake B	1.0
Total background	12.4
Data	11

1/12

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Events w/one tag 1 fb^{-1}	
Signal	0.44
Z+bb	35
Z+fake B	32
Total background	102
Data	100

1/200

1/3

Events w/two tags 1 fb^{-1}	
Signal	0.23
Z+bb	6.3
Z+fake B	1.0
Total background	12.4
Data	11

1/50

1/12

SELECTED Z + JETS
+ TWO B-TAGS

Higgs events : Everything else

one tag 0.5 : 100

1 : 200

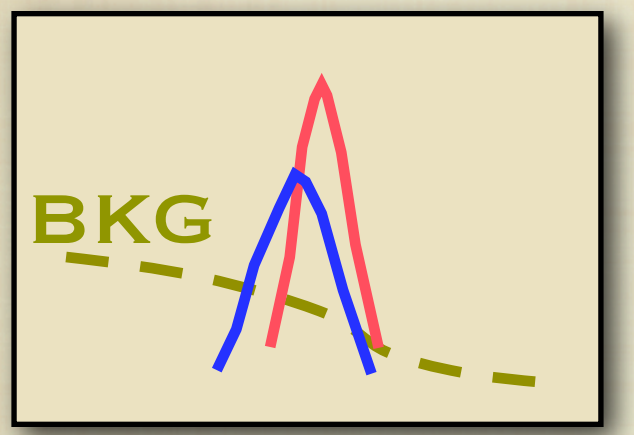
two tags 0.2 : 10

1 : 50

in 1 fb^{-1} data

Distinguishing Z+jets from ZH

- Best sensitivity to H→bb should be with M_{bb}
  - Easier to find Higgs if dijet mass resolution is narrower



Less background
under narrower signal

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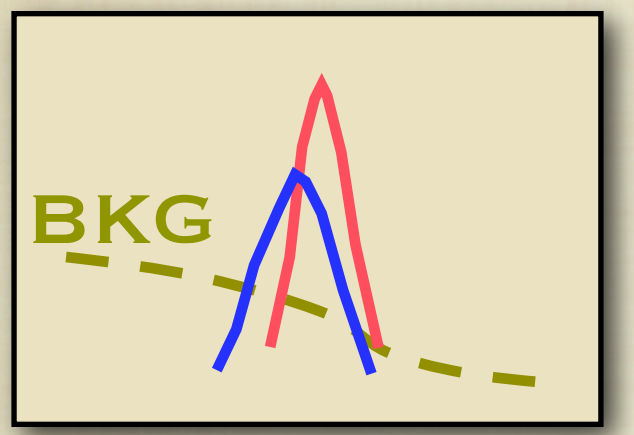

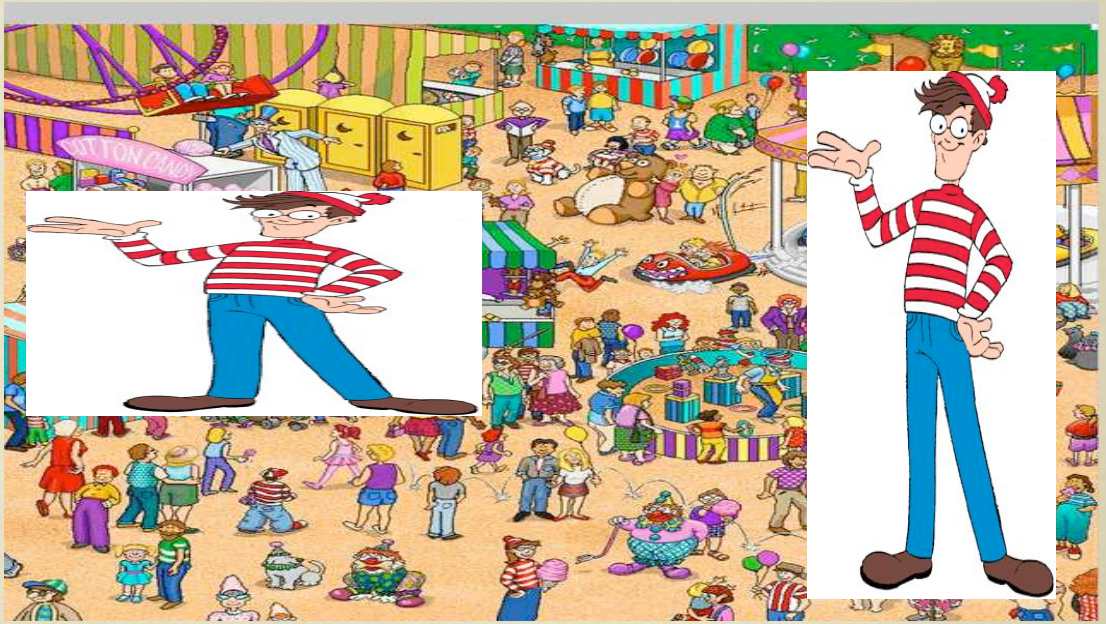

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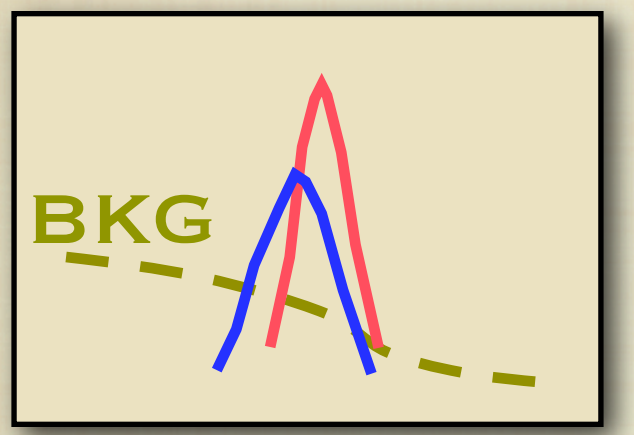

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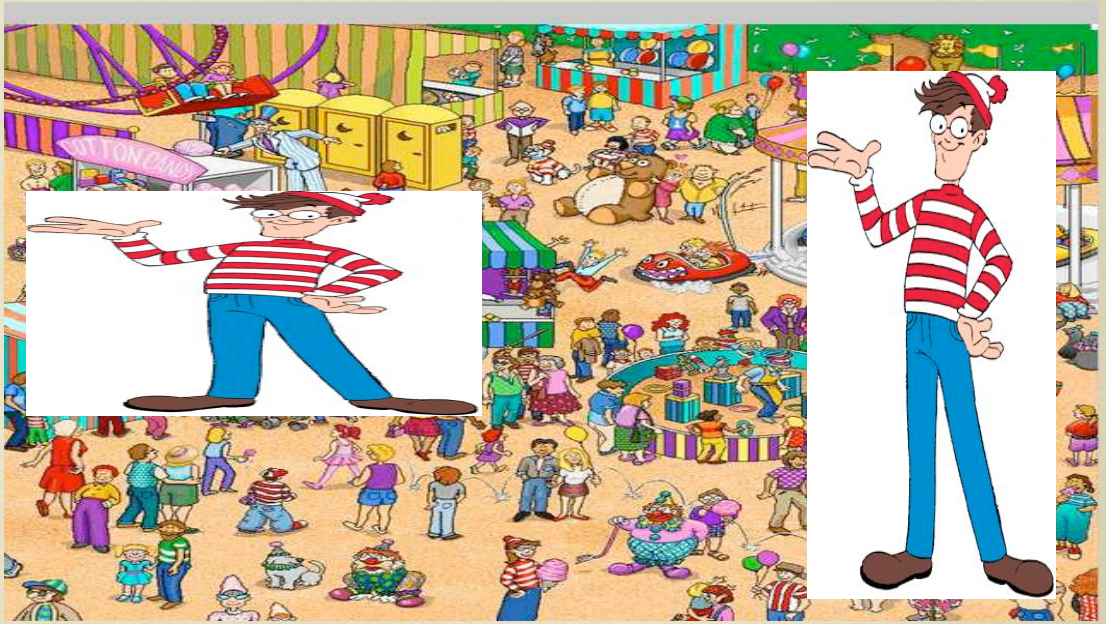

Where's Higgs ?

Using MET to improve M_{jj}

- In ZH → llbb, there should be no missing transverse energy
  - Leptons measured well
  - MET results from mismeasured jets

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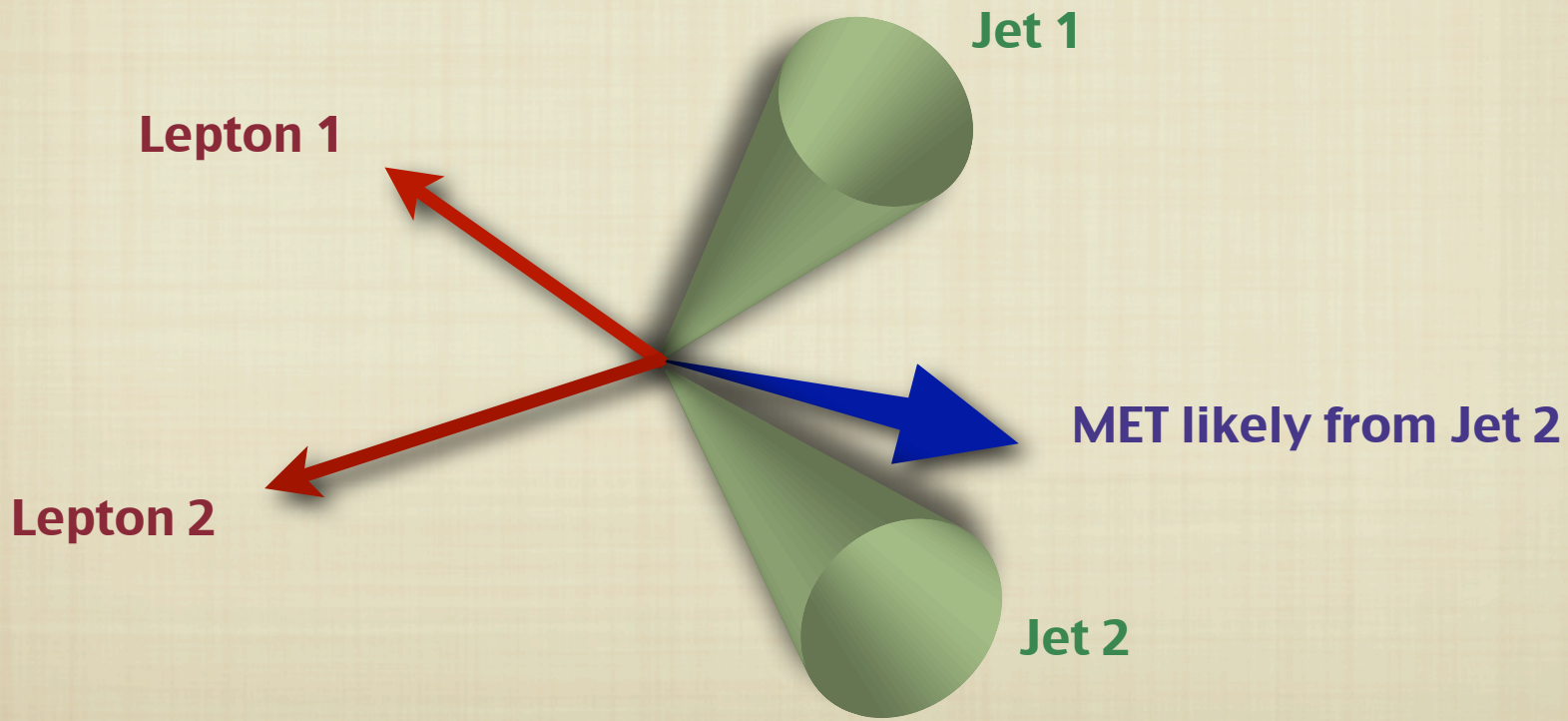

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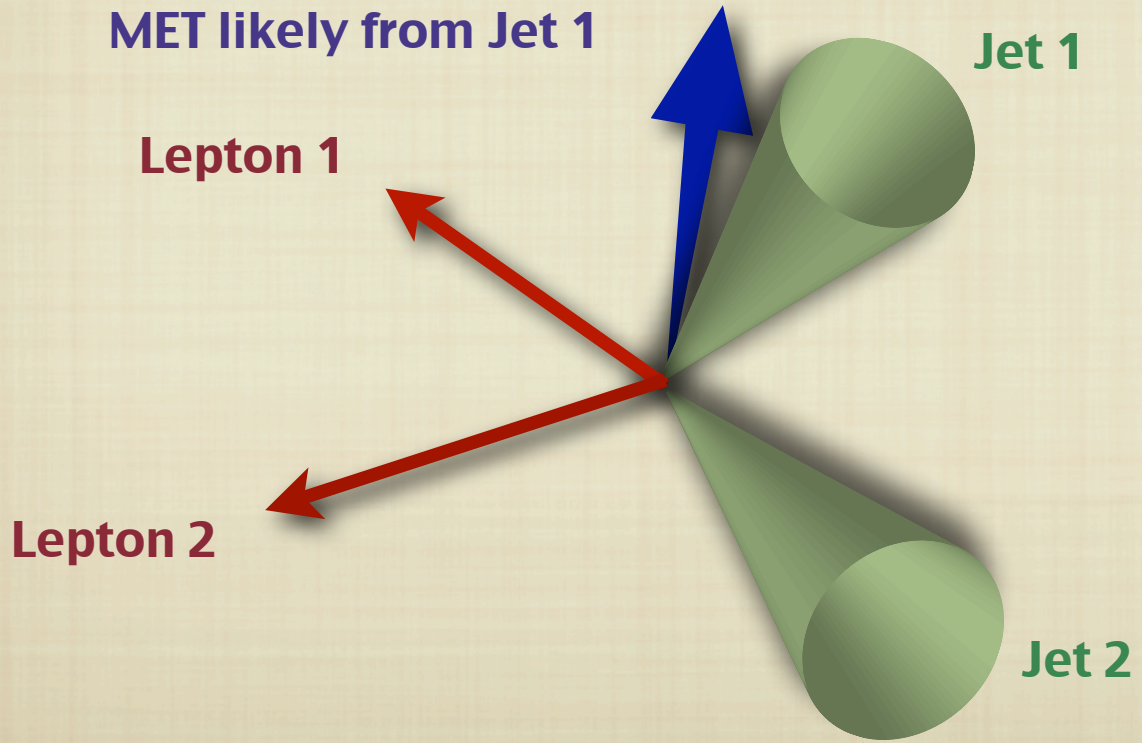

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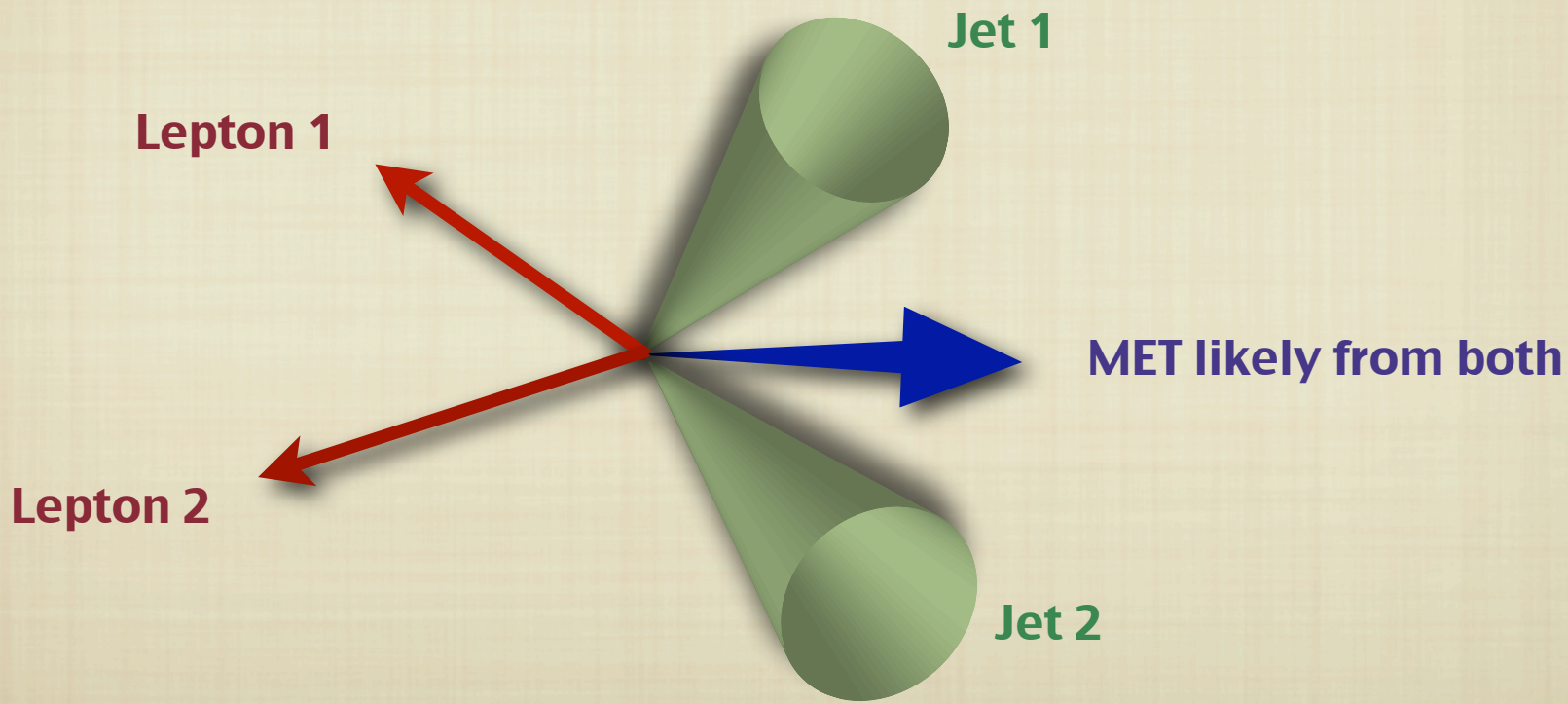

Dijet energy fitting function

- Goal is to correct jet energies to parton level
  - Improve dijet mass resolution
- (Jet 1 E_T, Jet 2 E_T) = function (Jet variables, MET variables)
  - Jet variables : E_T, η, ϕ, jet projection onto MET direction
  - MET variables : magnitude and ϕ

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- (Jet 1 E_T, Jet 2 E_T) = function (Jet variables, MET variables)
  - Jet variables : E_T, η, ϕ, jet projection onto MET direction
  - MET variables : magnitude and ϕ
- How to determine above variable correlations ?
  - We use an Artificial Neural Network
    - Will refer to as "NN"
  - Training NN
    - Inputs: Jet and MET variables + parton energies
    - Samples: ZH Monte Carlo for $60 < m_H < 180$ GeV
    - Outputs: corrected Jet 1 and Jet 2 energies

NN for jet energy corrections

- Example: Determine jet scale factors as function of MET ϕ (everything else fixed)

MET : 20 GeV

Jet 1 :

$\phi = \pi/2$

$E_T = 85$ GeV

$\eta = 1.0$

Jet 2 :

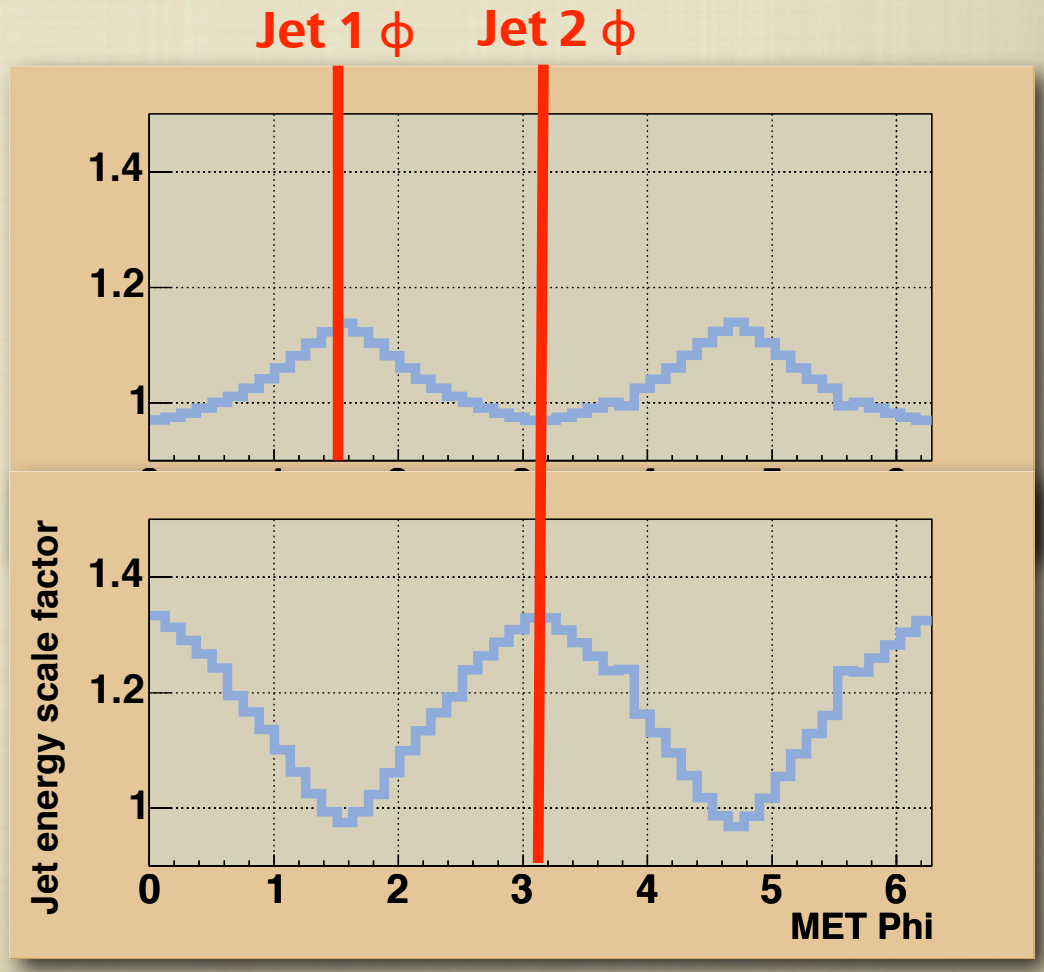
$\phi = \pi$

$E_T = 45$ GeV

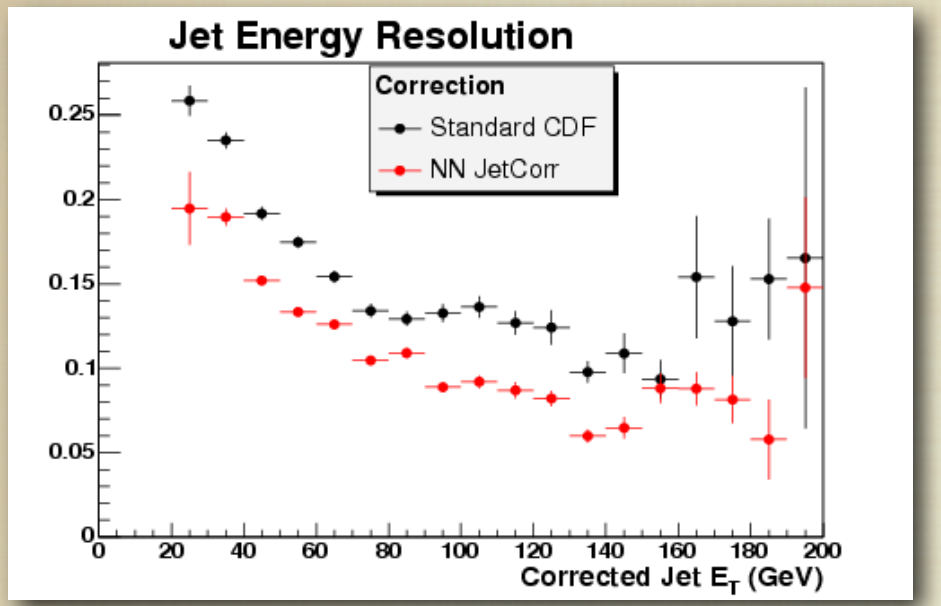
$\eta = 1.0$

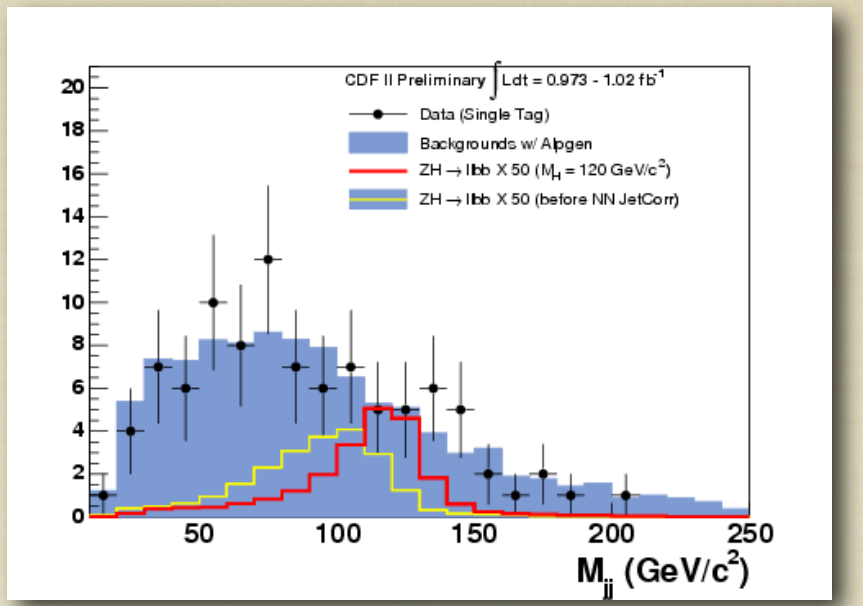
Jet 1 scale factor

Jet 2 scale factor



Resulting M_{jj} improvement





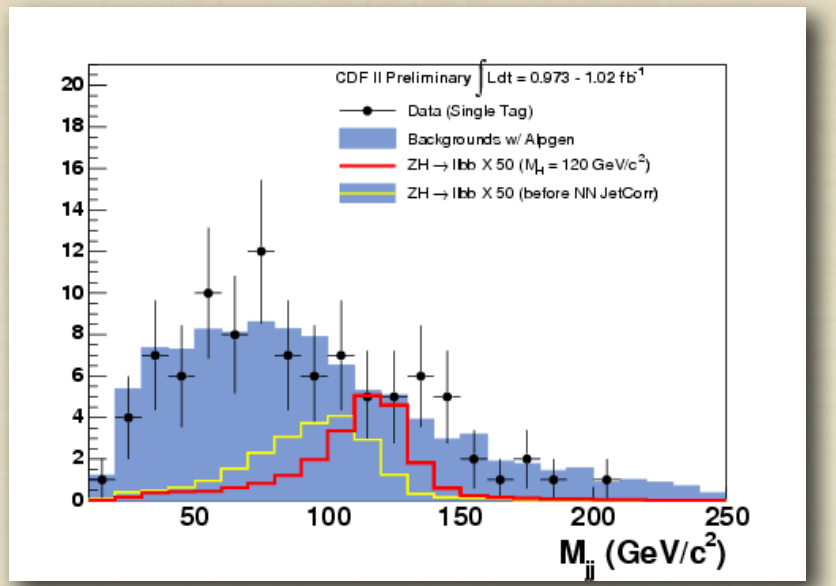
M_{JJ} one b-tag data

- Validation using Z+jets data before b-tag
  - Compare jet energies, dijet mass, MET distribution
  - Energy resolution verified by balancing dijet recoil against Z boson
- For events w/ two b-tags, dijet mass resolution improves from 18% to 11%

Separating Higgs from background

Multivariate Higgs identification

- Dijet mass is good discriminant but not best



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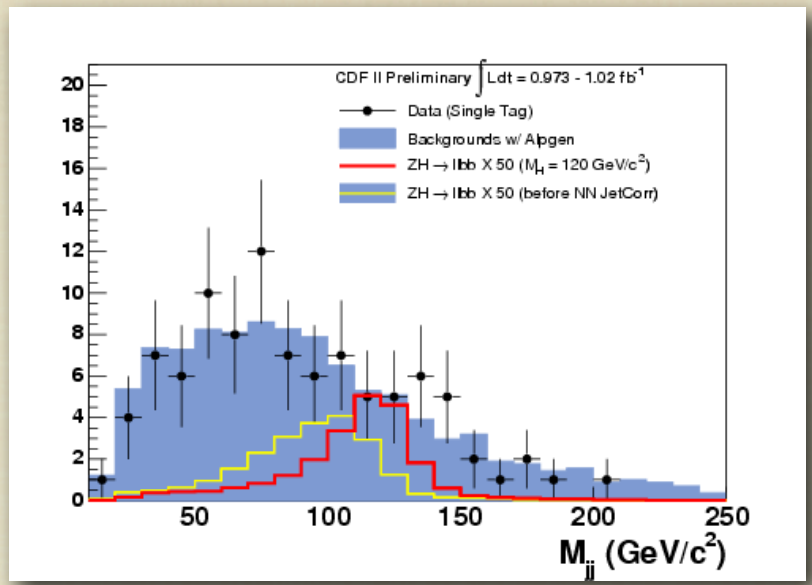
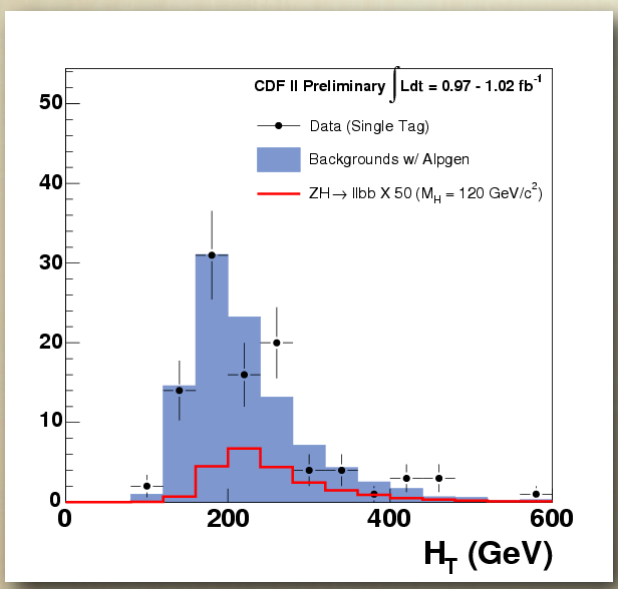
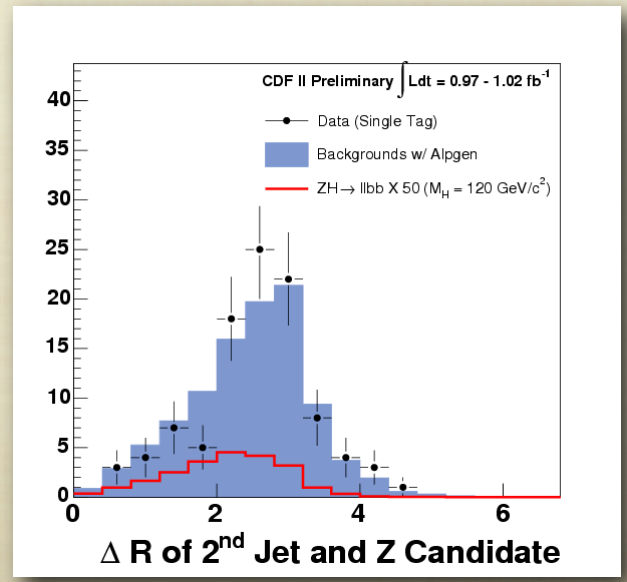
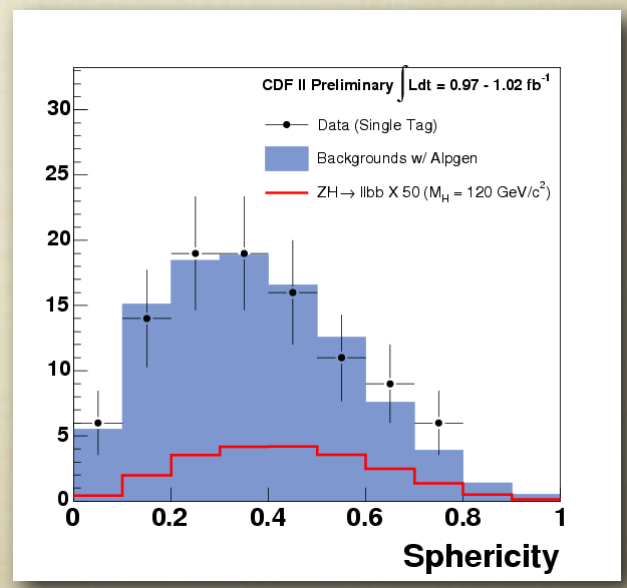


- Better to use multiple distributions which all separate signal from background

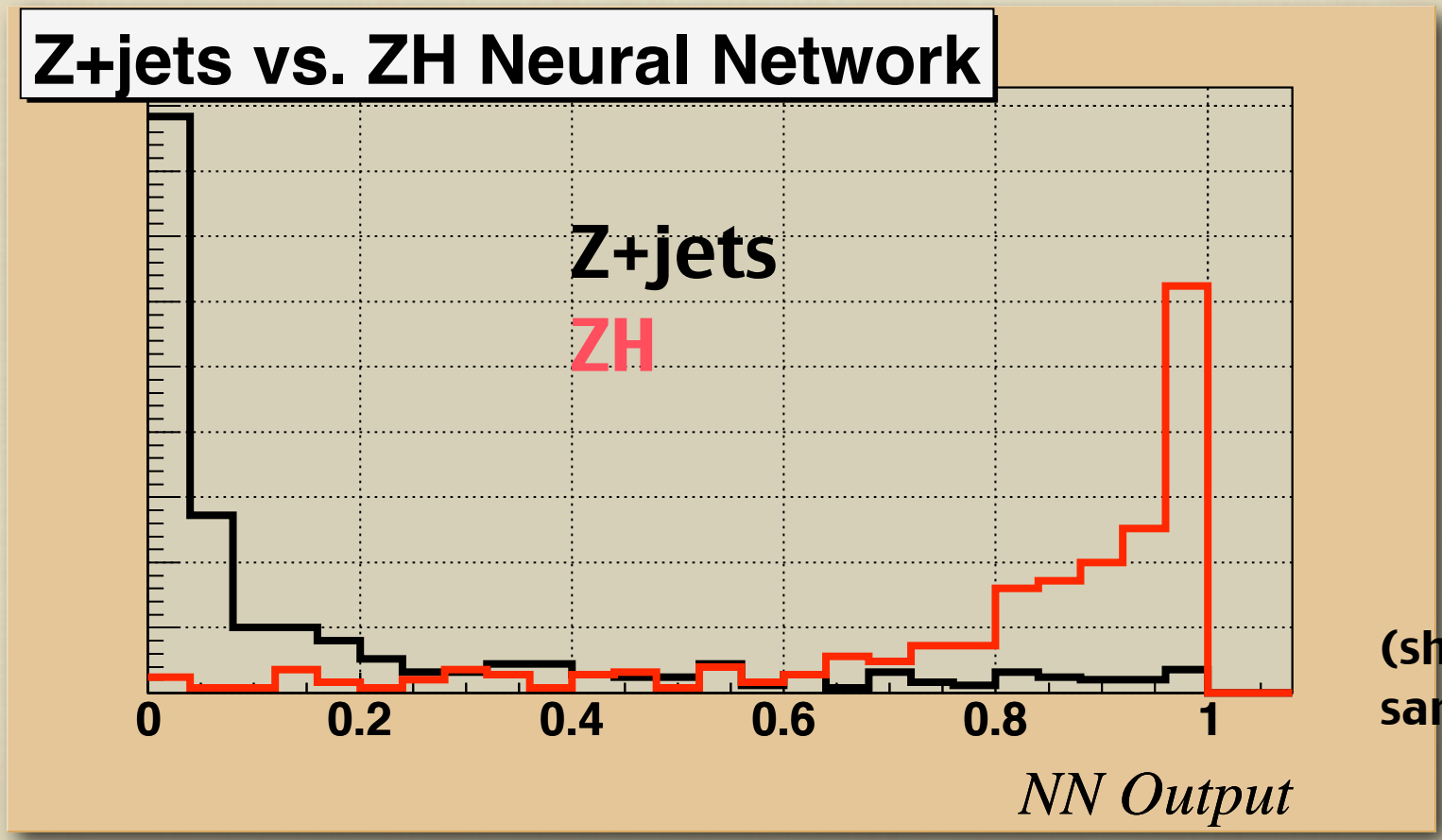






Separate ZH from Z+jets

- NN Network trained to distinguish Z+jets and ZH

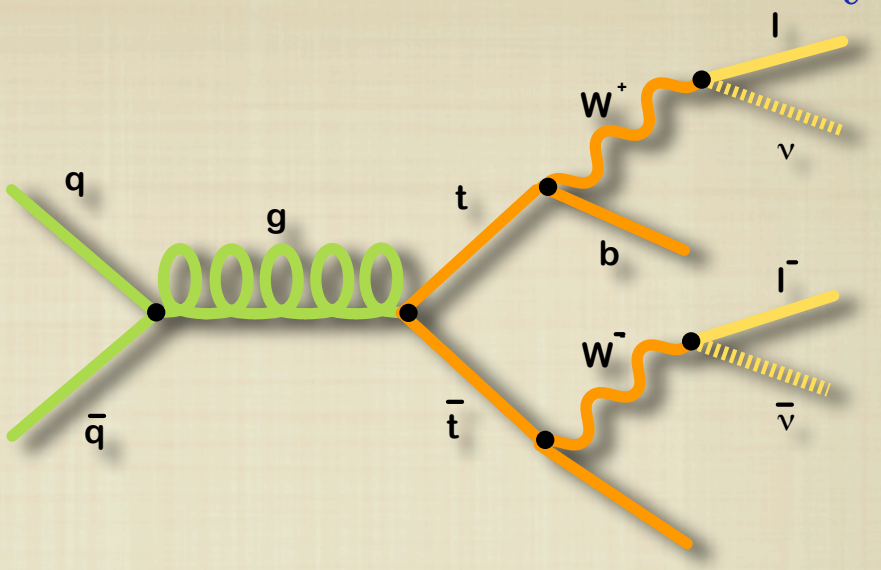


(shown with same area)

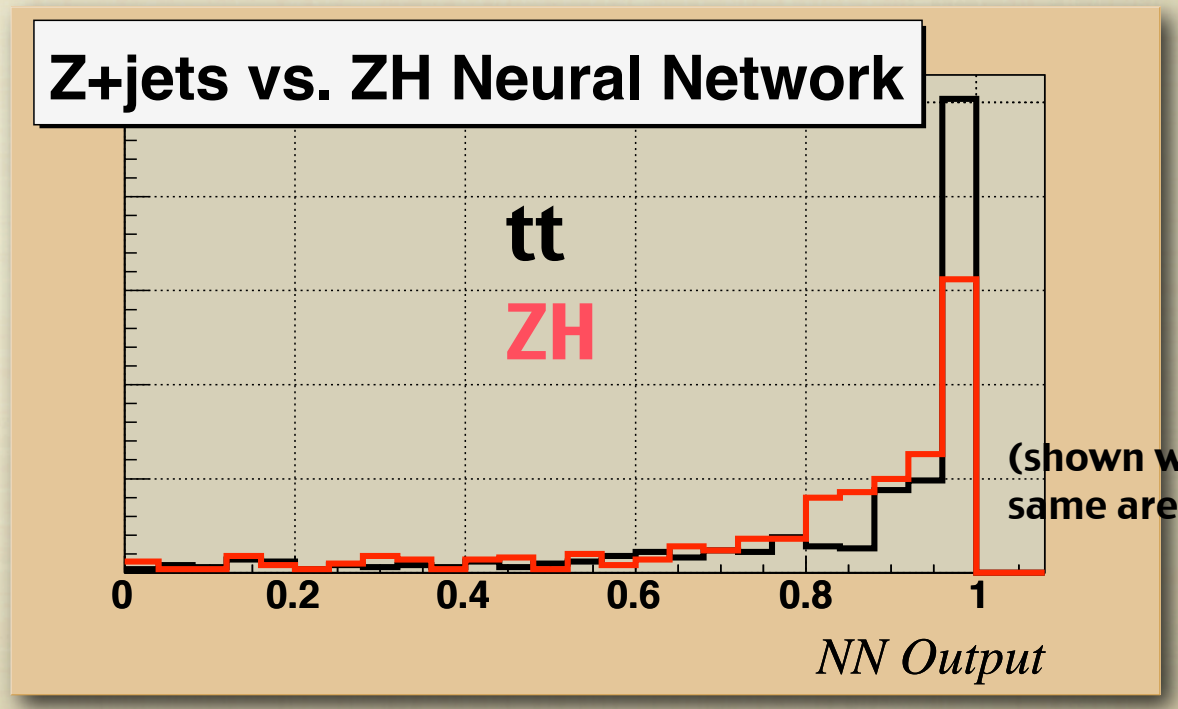
Separation much better than dijet mass alone

The top problem

- Two leptons, two b quarks, two neutrinos
  - Neutrinos may decay back to back
  - High sum E_T events

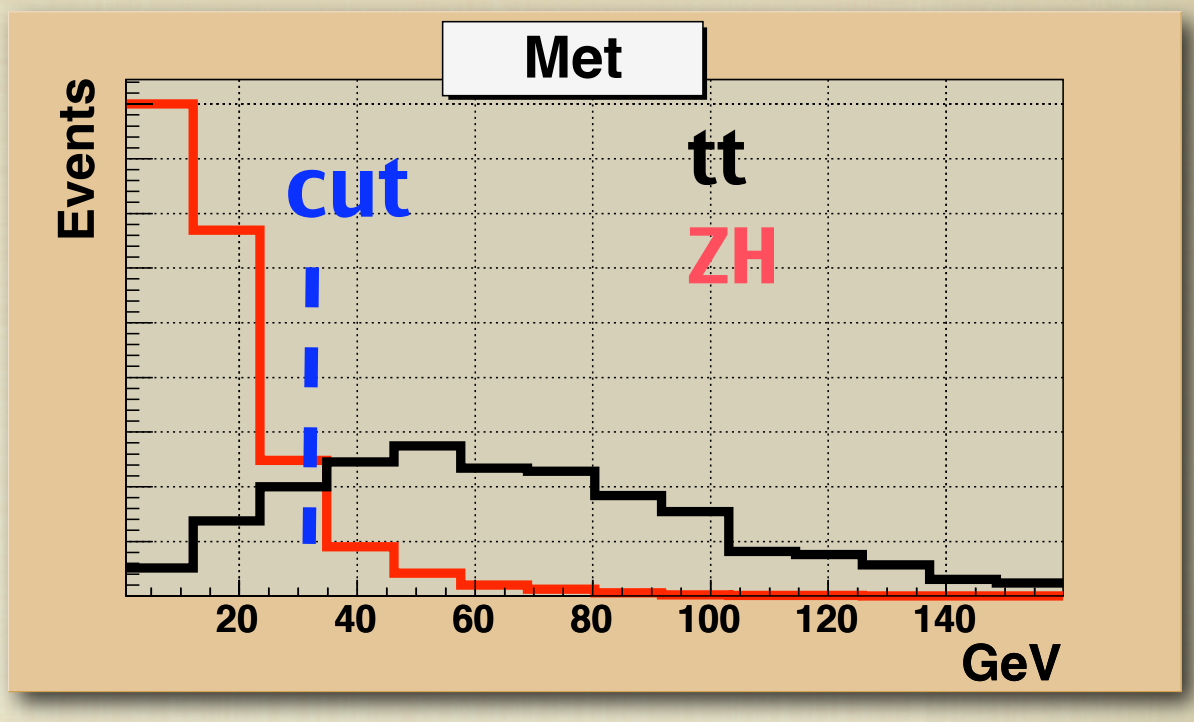


- tt looks more like ZH than ZH does !
- tt is 20% of background in 2-tag data
- 10 times the size of ZH



How to reject top

- **Remove events with MET > 33 GeV**
  - Rejects 80% tt
  - Rejects only 10% ZH



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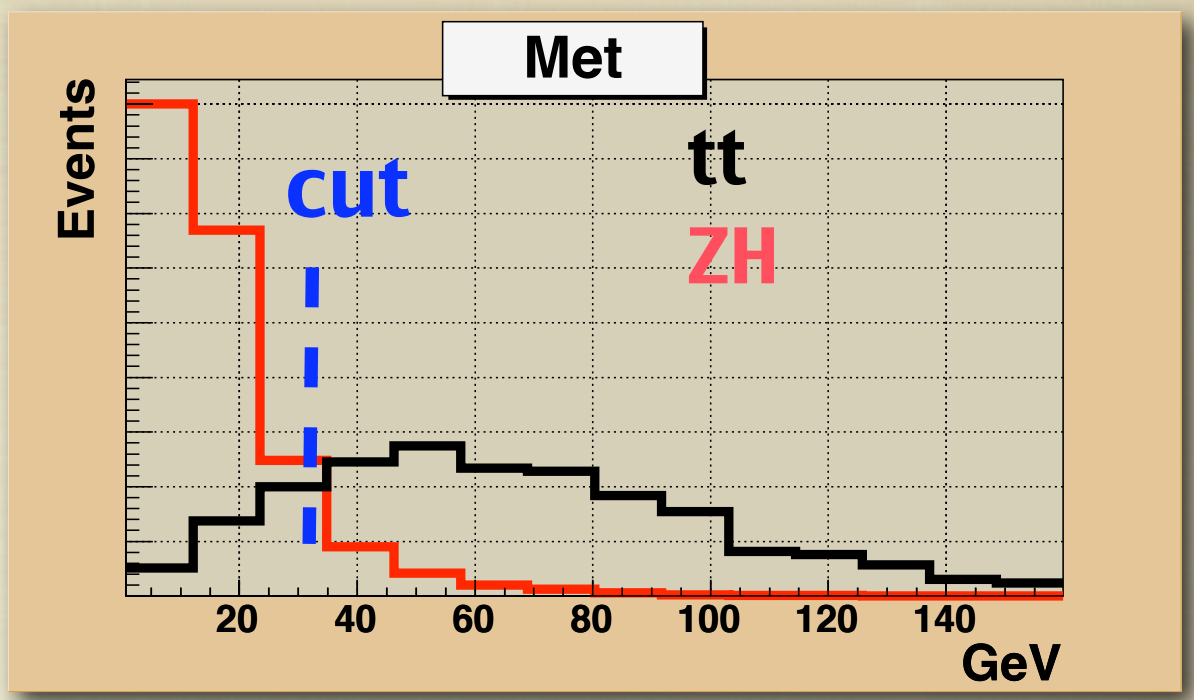
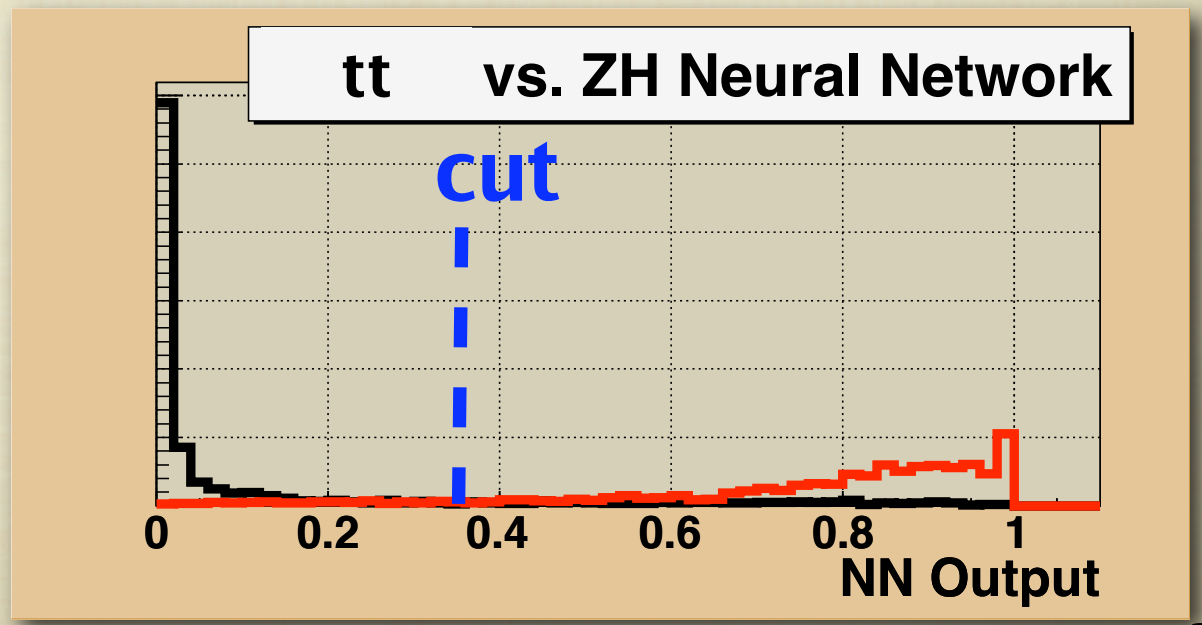


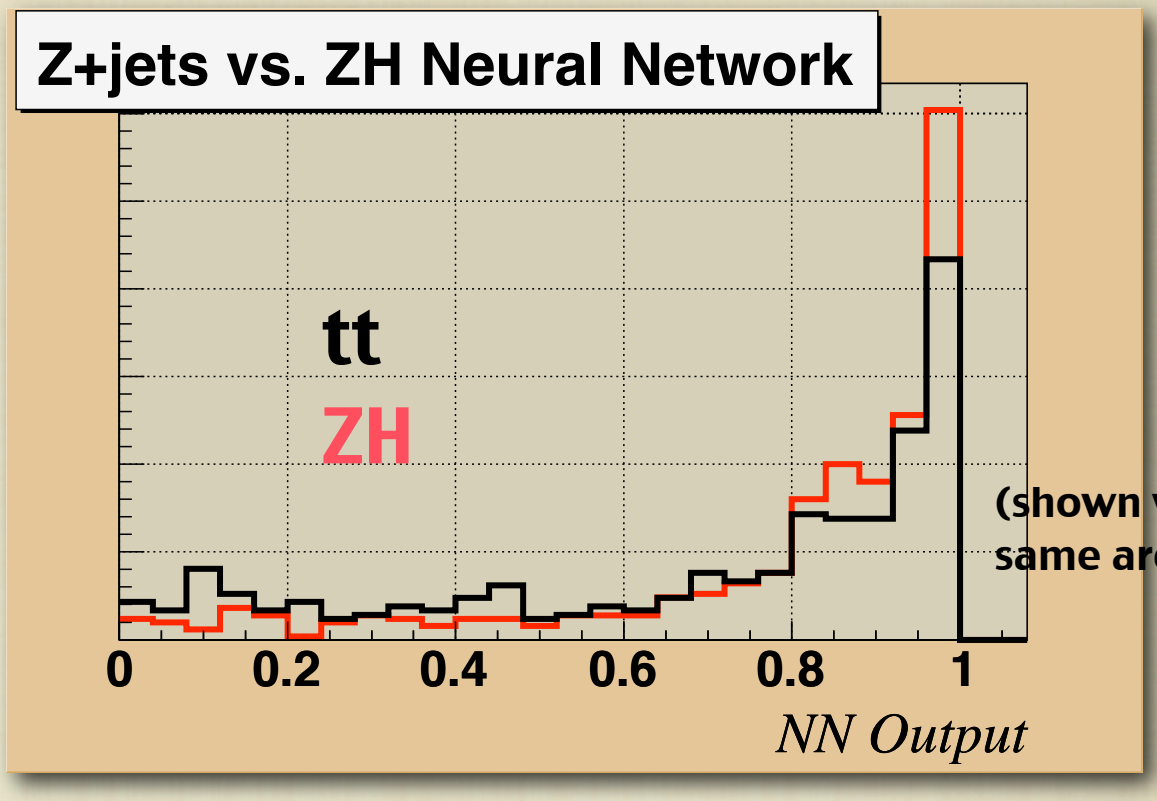
- Train NN to separate ZH vs tt
  - Rejects 80% tt
  - Rejects only 5 % ZH



What's left of top ?

- Remaining tt events look like this for either cut :

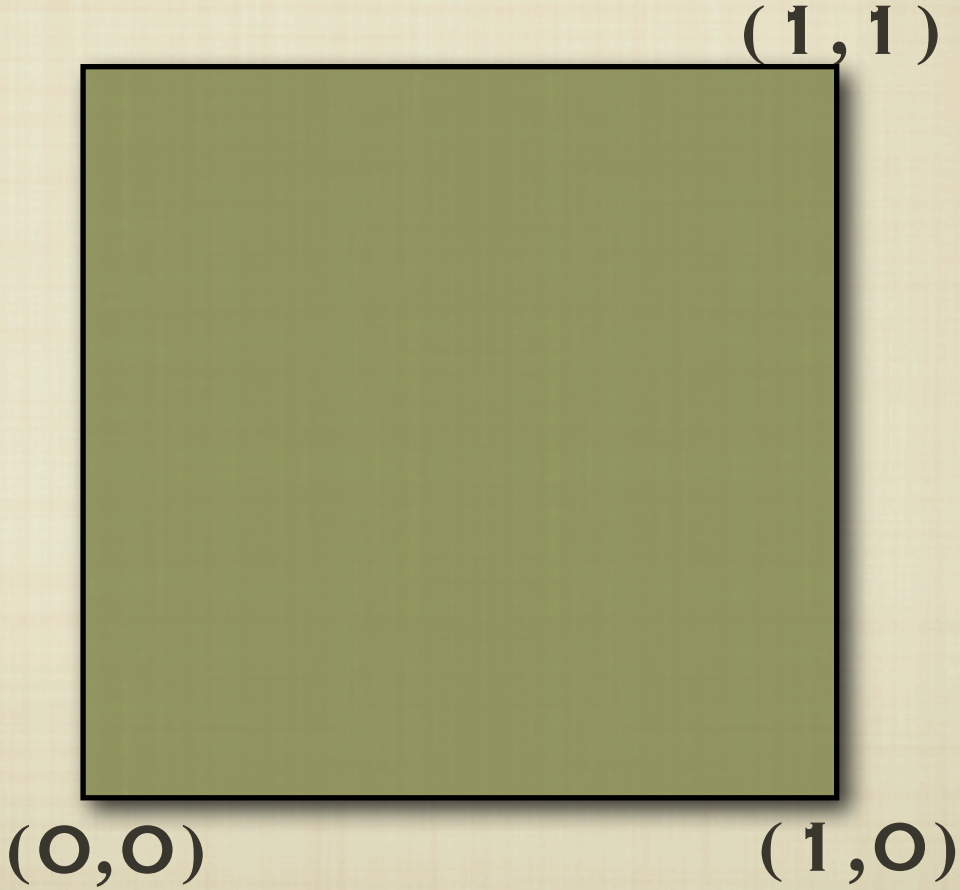
ZH & tt have same shape in the Z+jets NN



- tt removal worsens limits
  - Loss of ZH signal efficiency
  - Remaining tt right in signal region
  - tt cross section becomes important systematic

Can Z+jets and tt be separated simultaneously ?

- Signal / Background discriminant with Two outputs

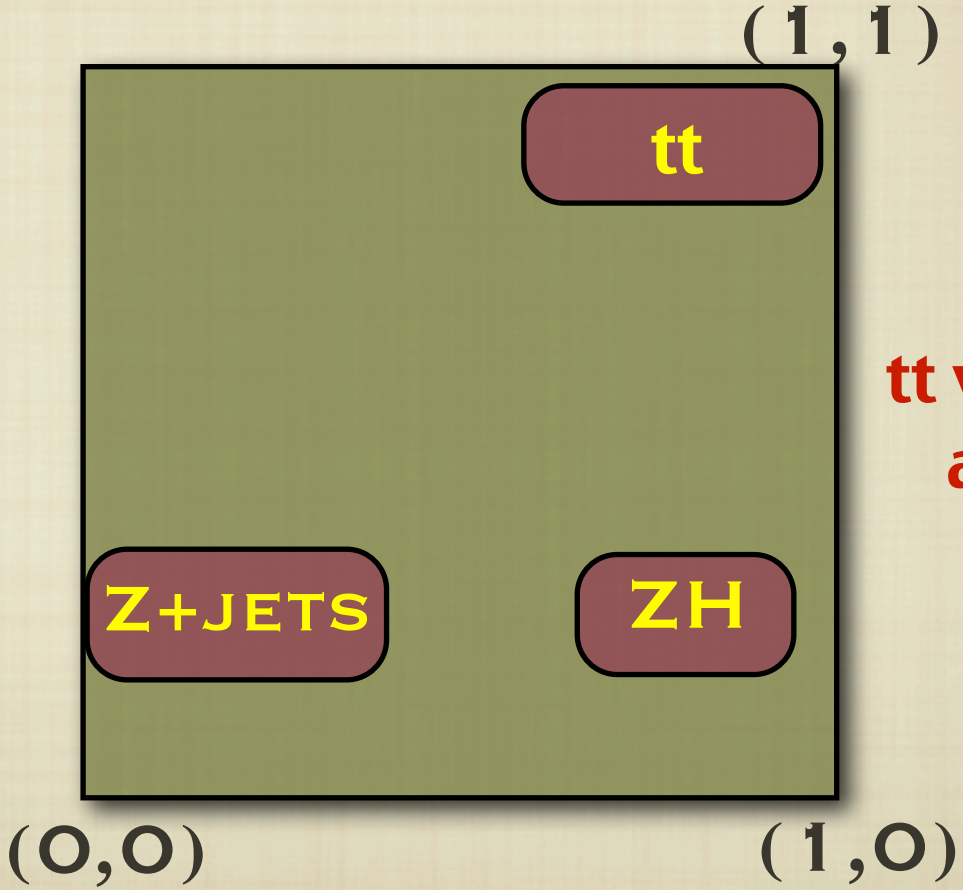


Can Z+jets and tt be separated simultaneously ?

- Signal / Background discriminant with Two outputs

2D NN

✦ Training: Z+bb, tt, ZH



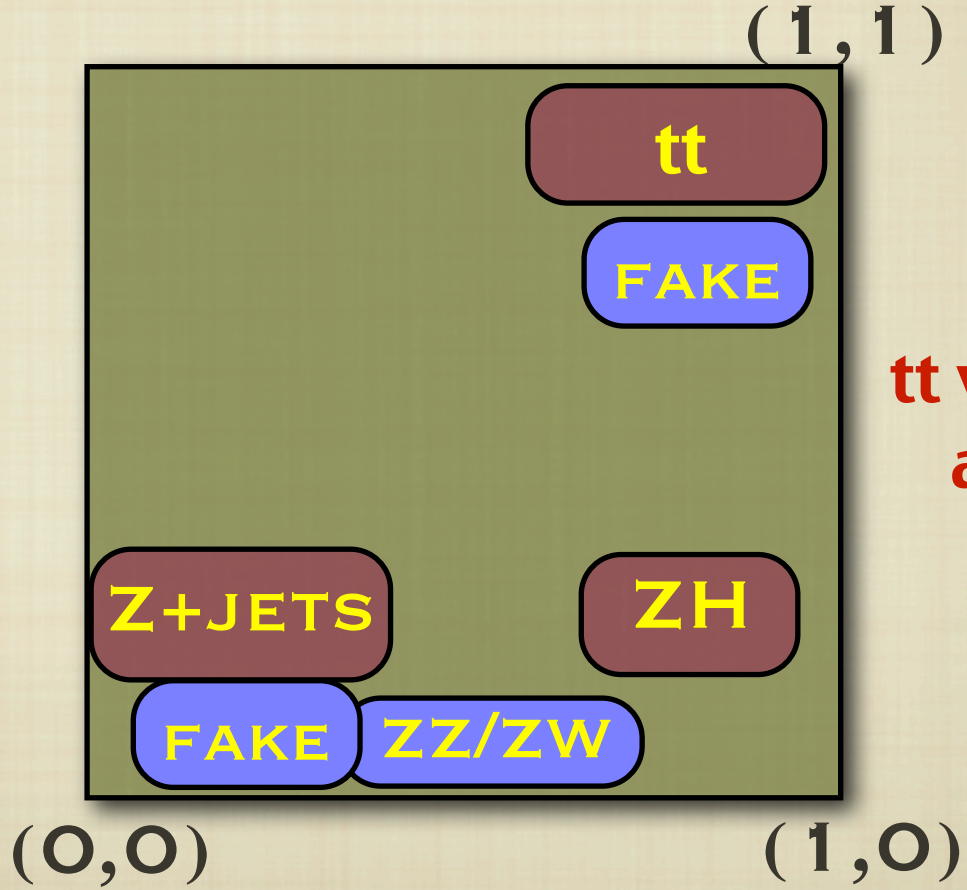
Can Z+jets and tt be separated simultaneously ?

- Signal / Background discriminant with Two outputs

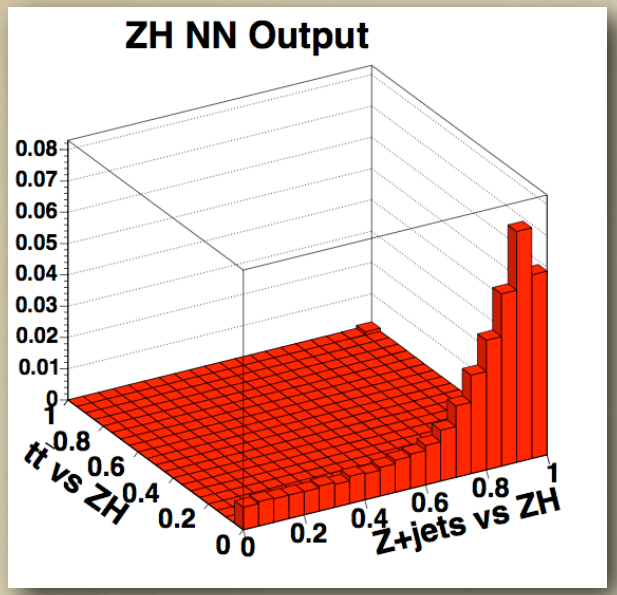
2D NN

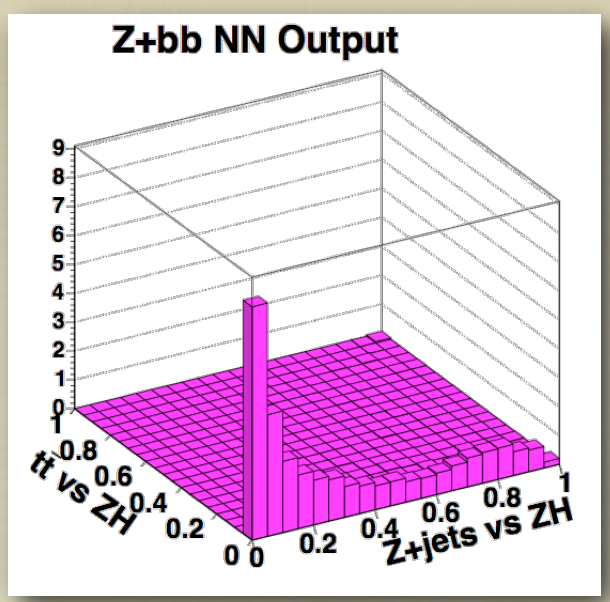
✦ Training: Z+bb, tt, ZH

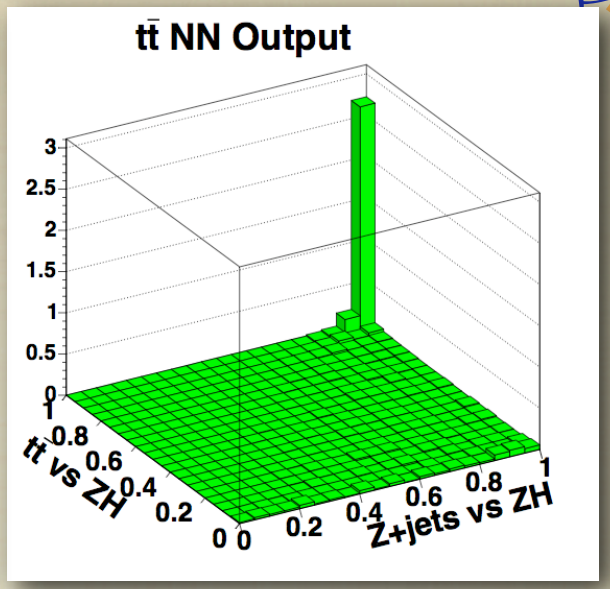
✦ Shapes generated in 2D plane also for fakes, Z +mistag, Z+cc, ZZ, ZW



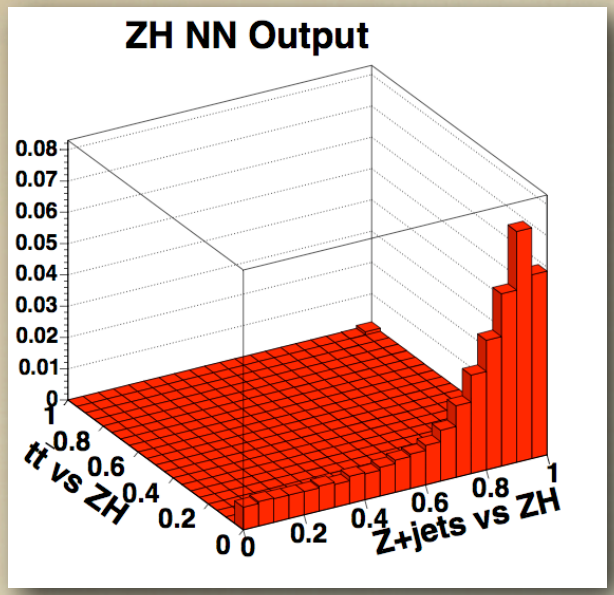
NN output for ZH well separated from Z+bb and tt

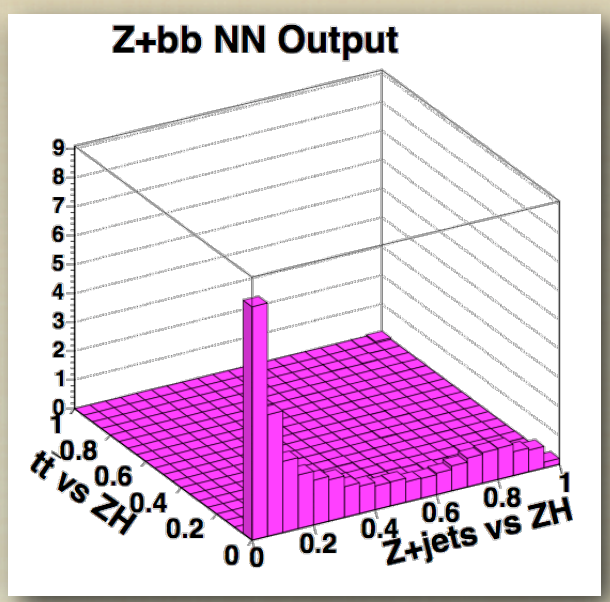


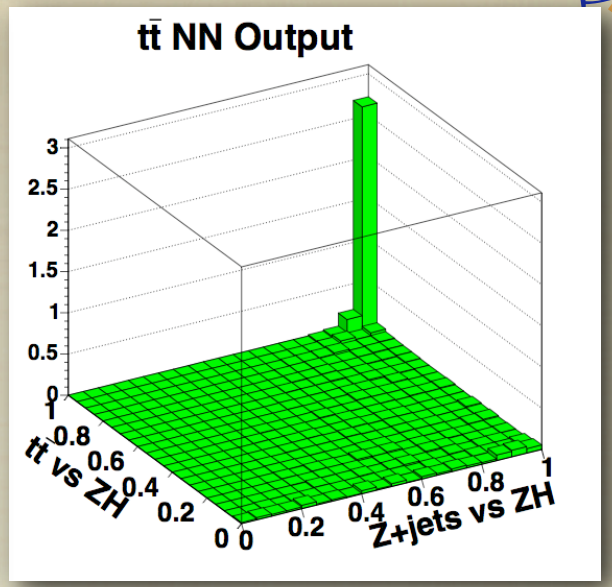




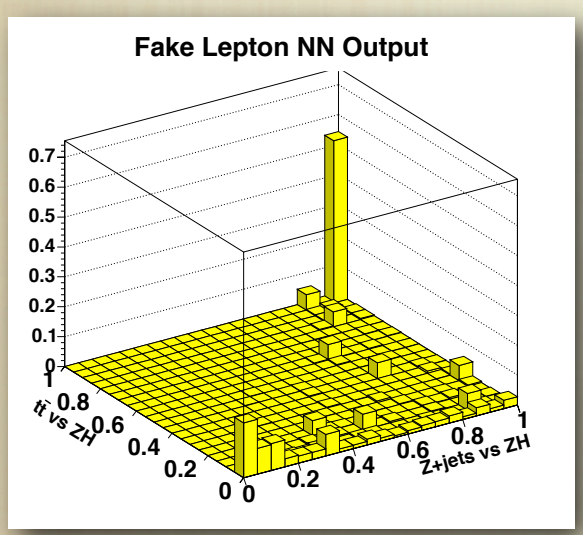
NN output for ZH well separated from Z+bb and tt

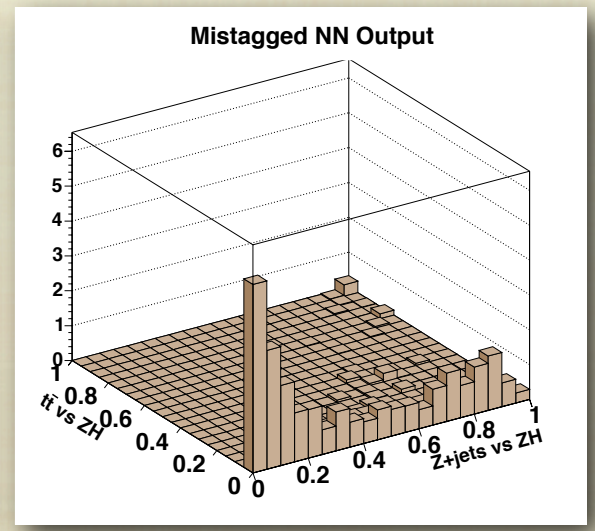






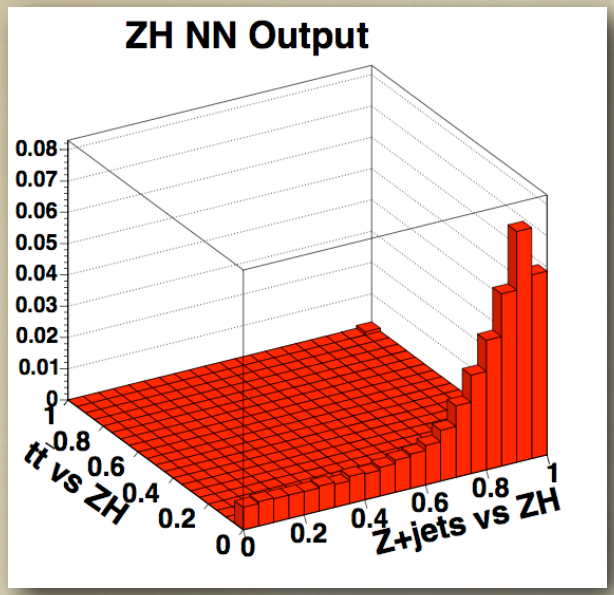
NN outputs determined from data

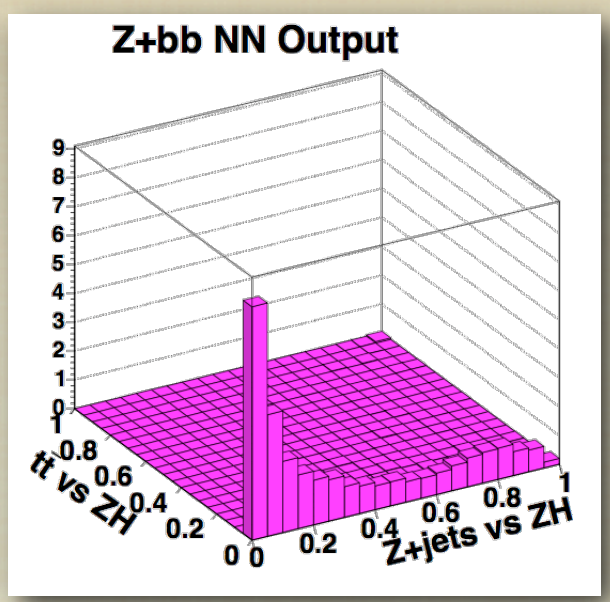


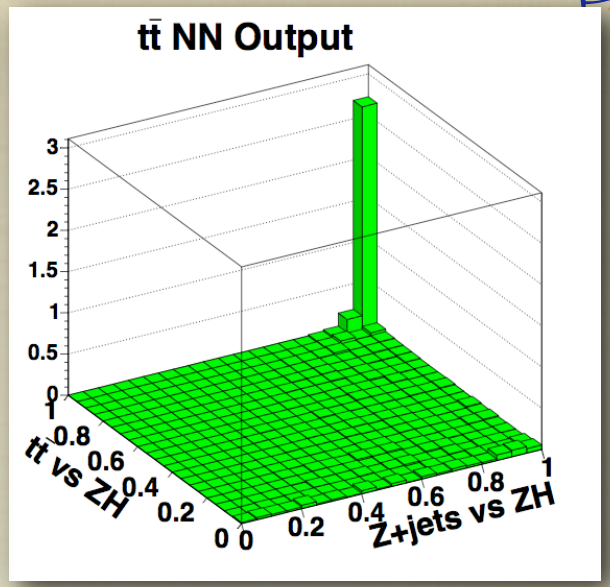


Fake Z's well separated

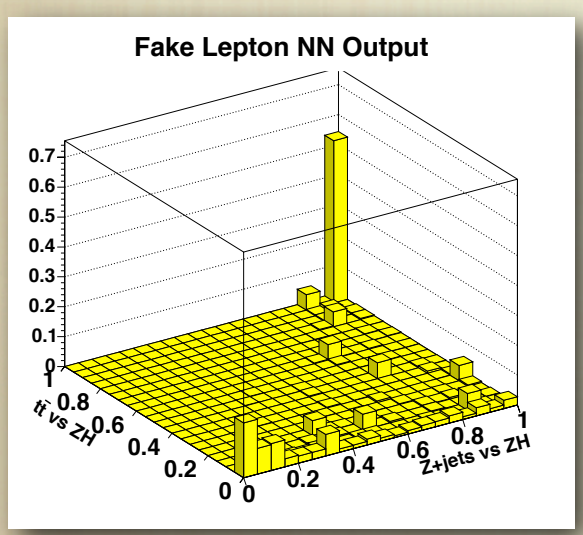
NN output for ZH well separated from Z+bb and tt

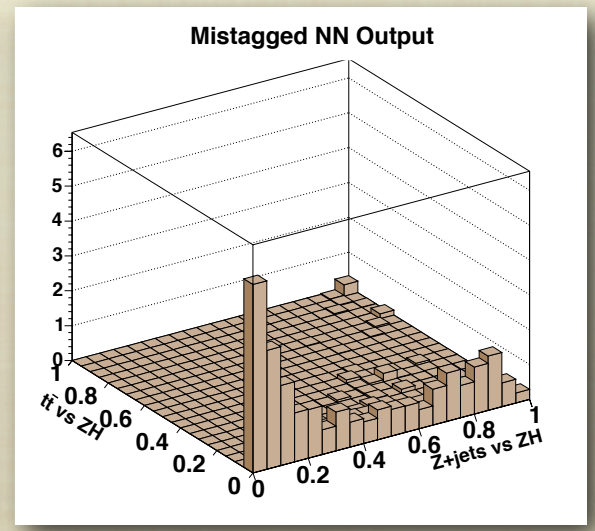


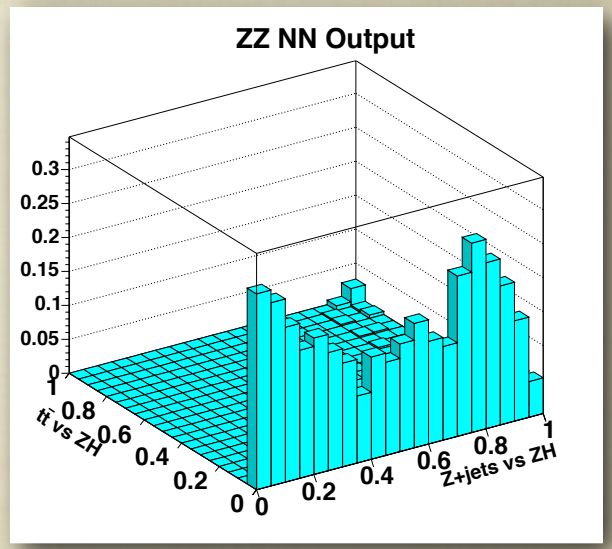




NN outputs determined from data







Fake Z's well separated

ZZ →llbb has shape most similar to ZH

SELECTED Z + JETS + SIGNAL REGION OF NN

Higgs events : Everything else

one tag 0.3 : 14

1 : 50

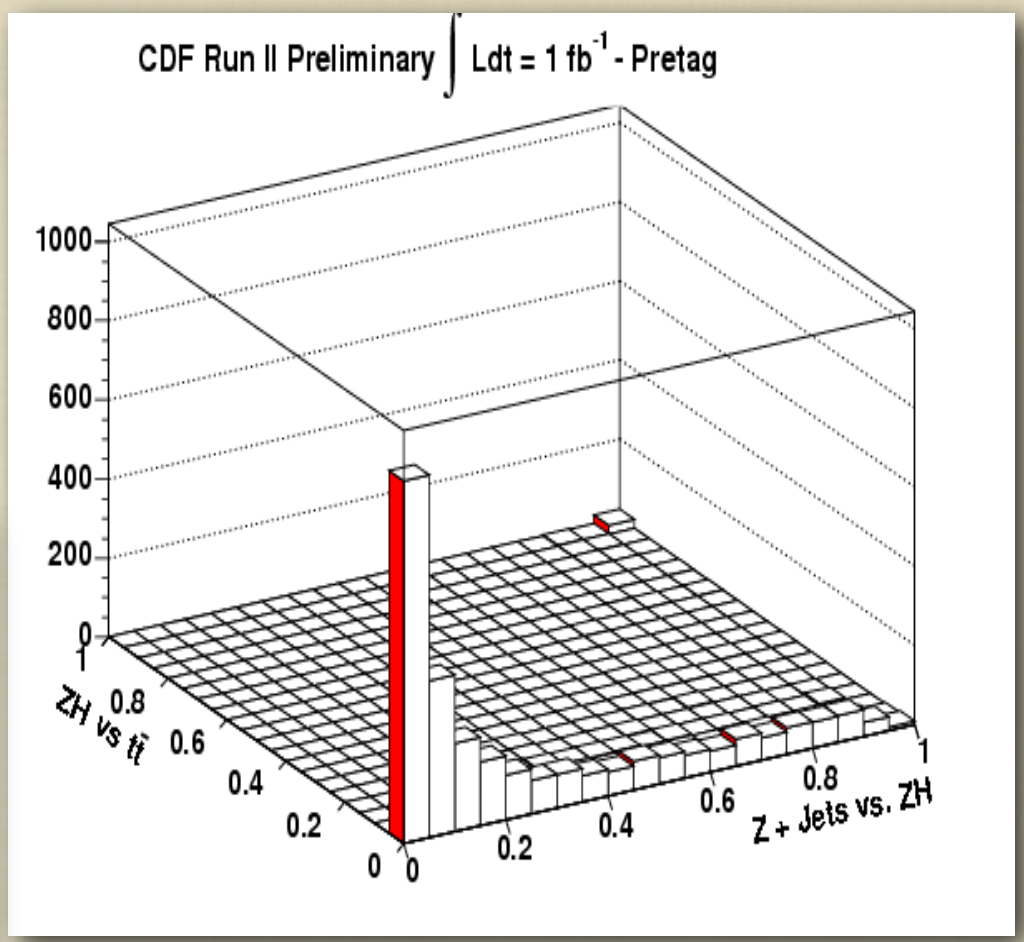
two tags 0.2 : 2

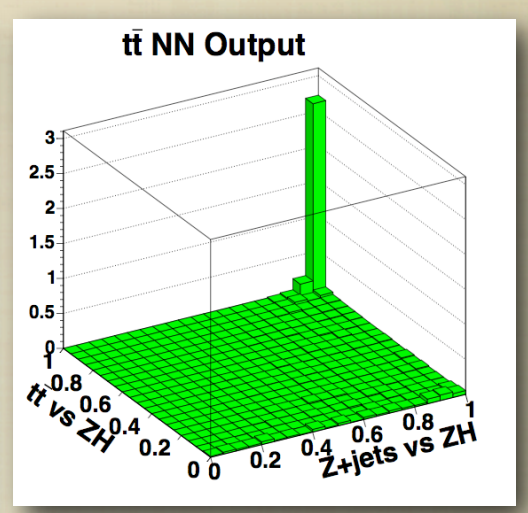
1 : 10

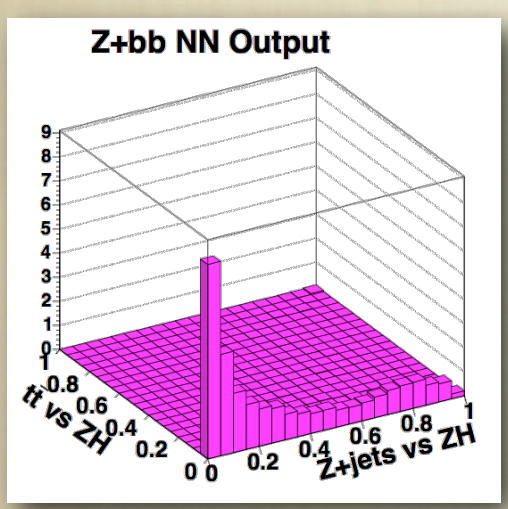
in 1 fb^{-1} data

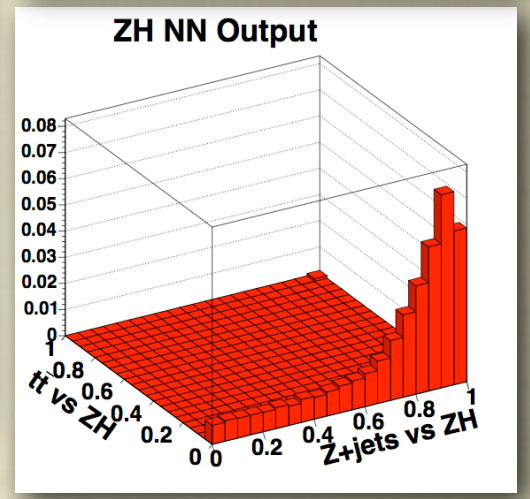
Data: Before b-tagging

Composed of
95% Z+jets





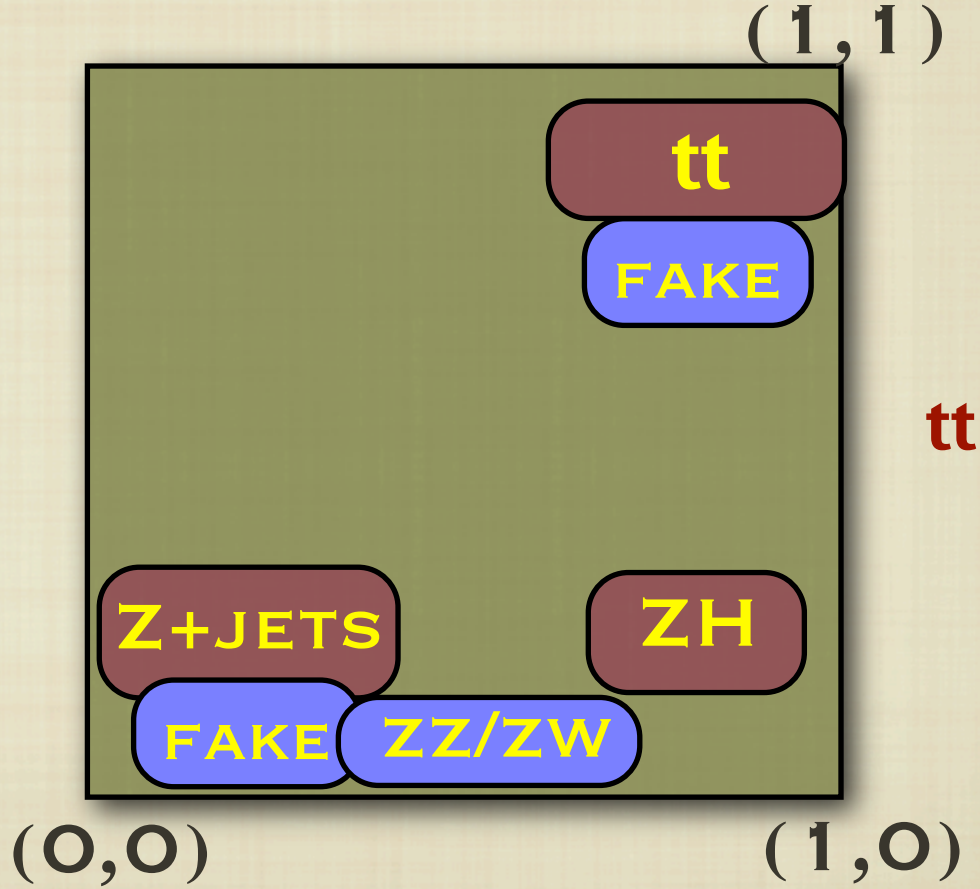




Data : 3000 events
useful for validating NN & background model

Validation of NN

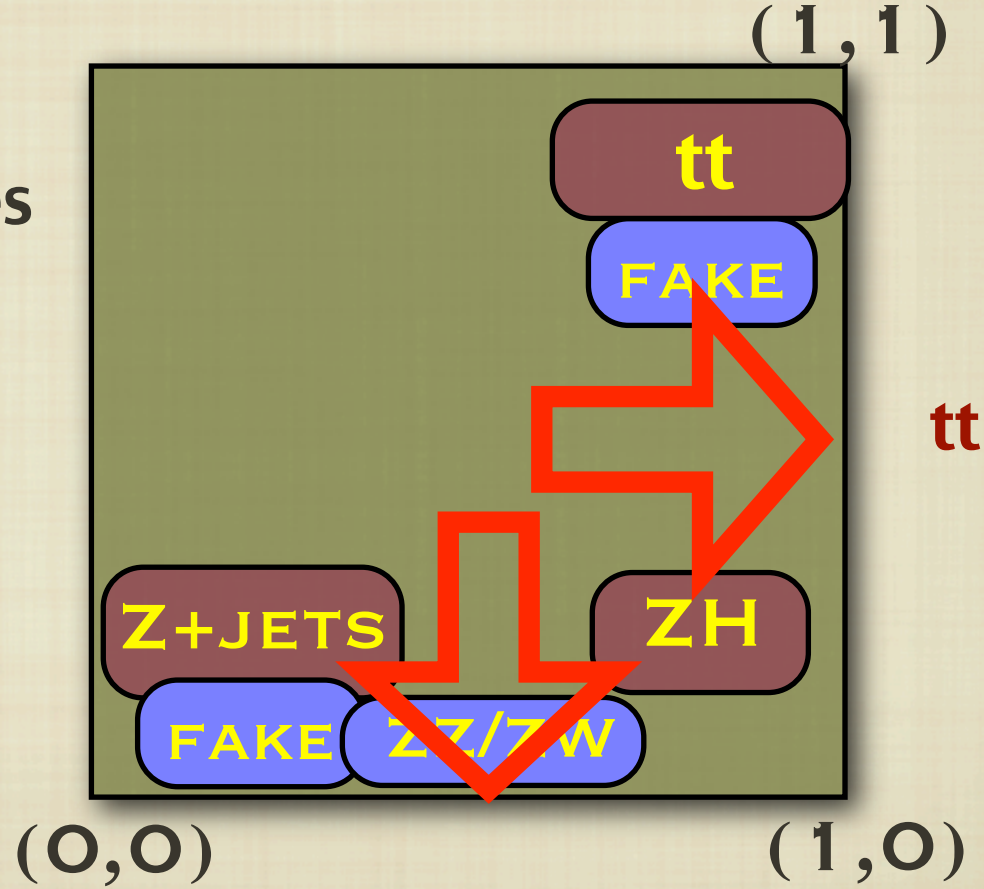
- We can project NN output into 1D to validate background model



Validation of NN

- We can project NN output into 1D to validate background model

- Projections onto axes
  "ZH vs. Z+jets"
  &
  "tt vs. ZH"

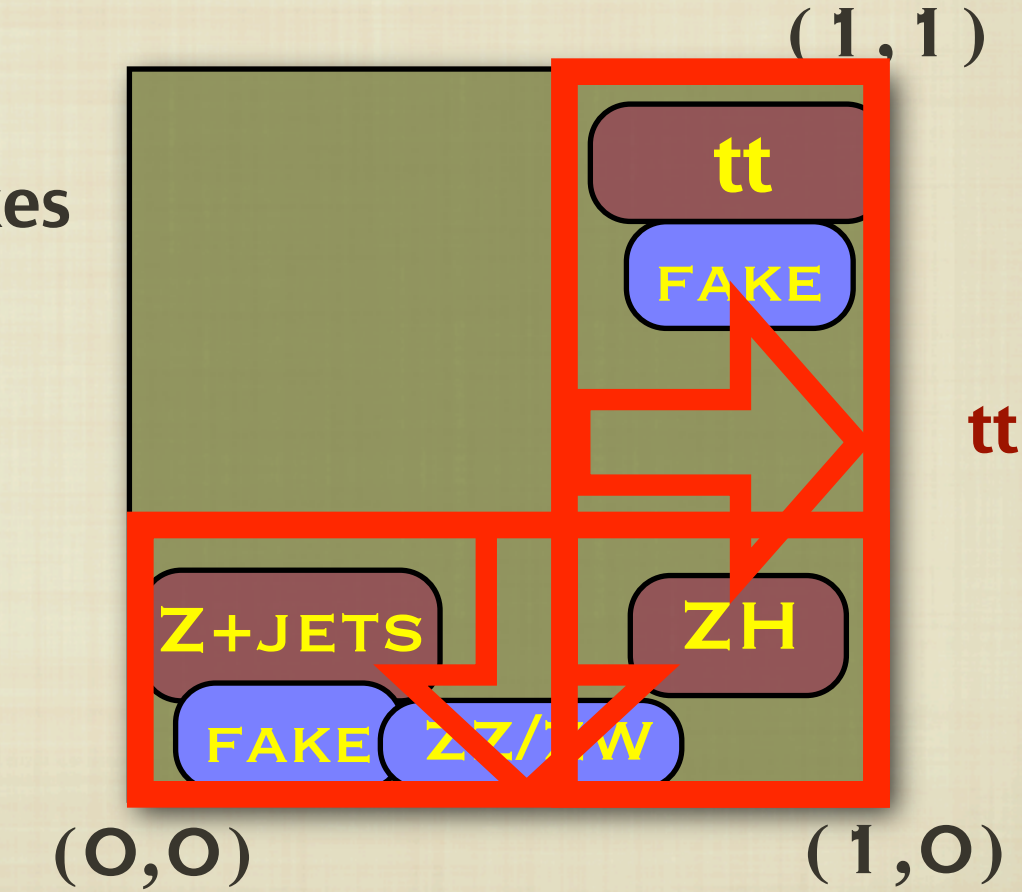


Validation of NN

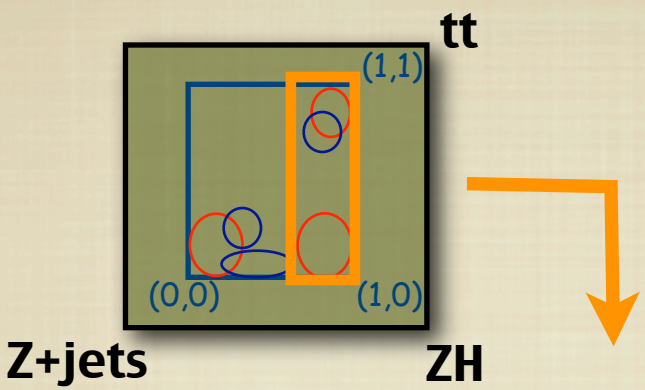
- We can project NN output into 1D to validate background model

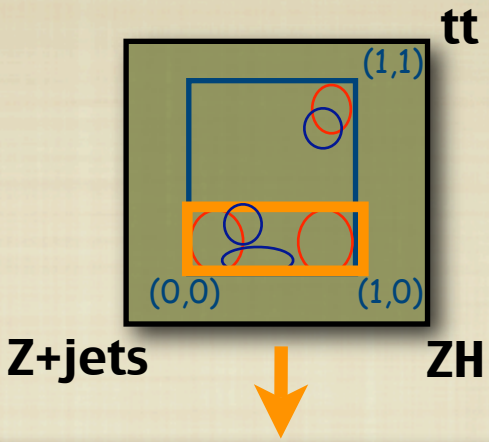
- Projections onto axes
  "ZH vs. Z+jets"
  &
  "tt vs. ZH"

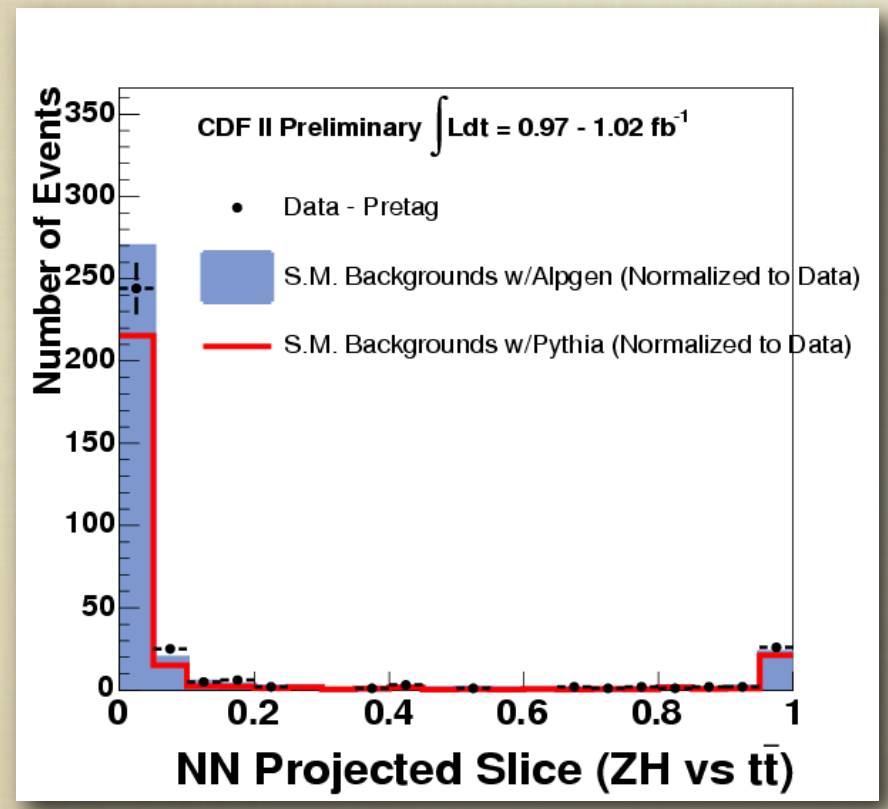
- Projections of slices along each axis

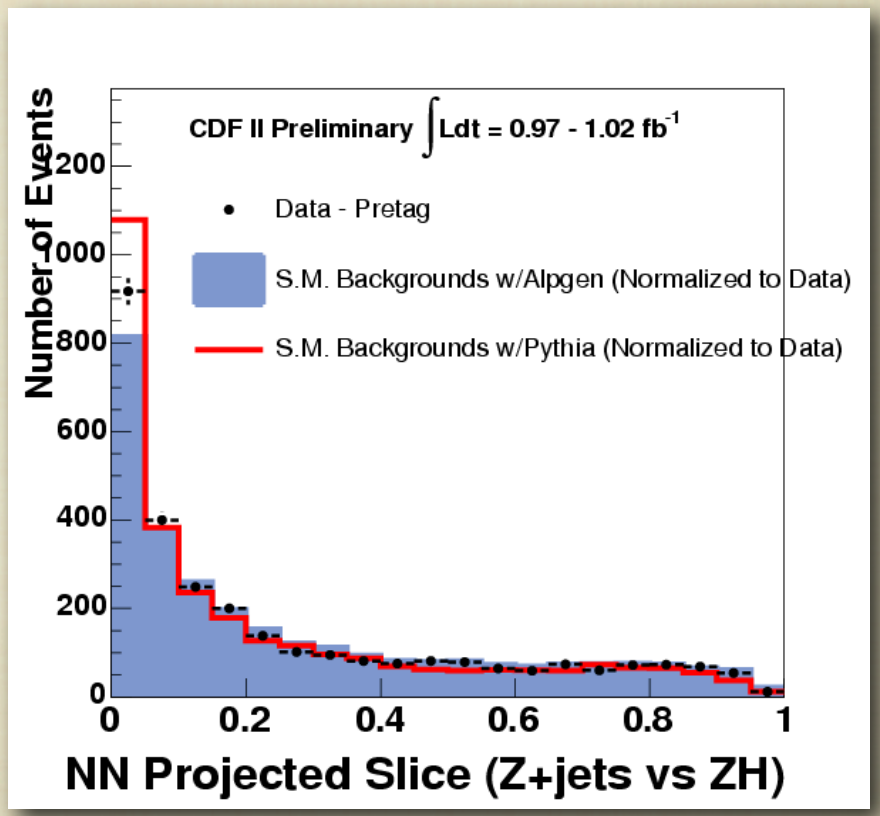


Projections of Z+jets no-tag control regions



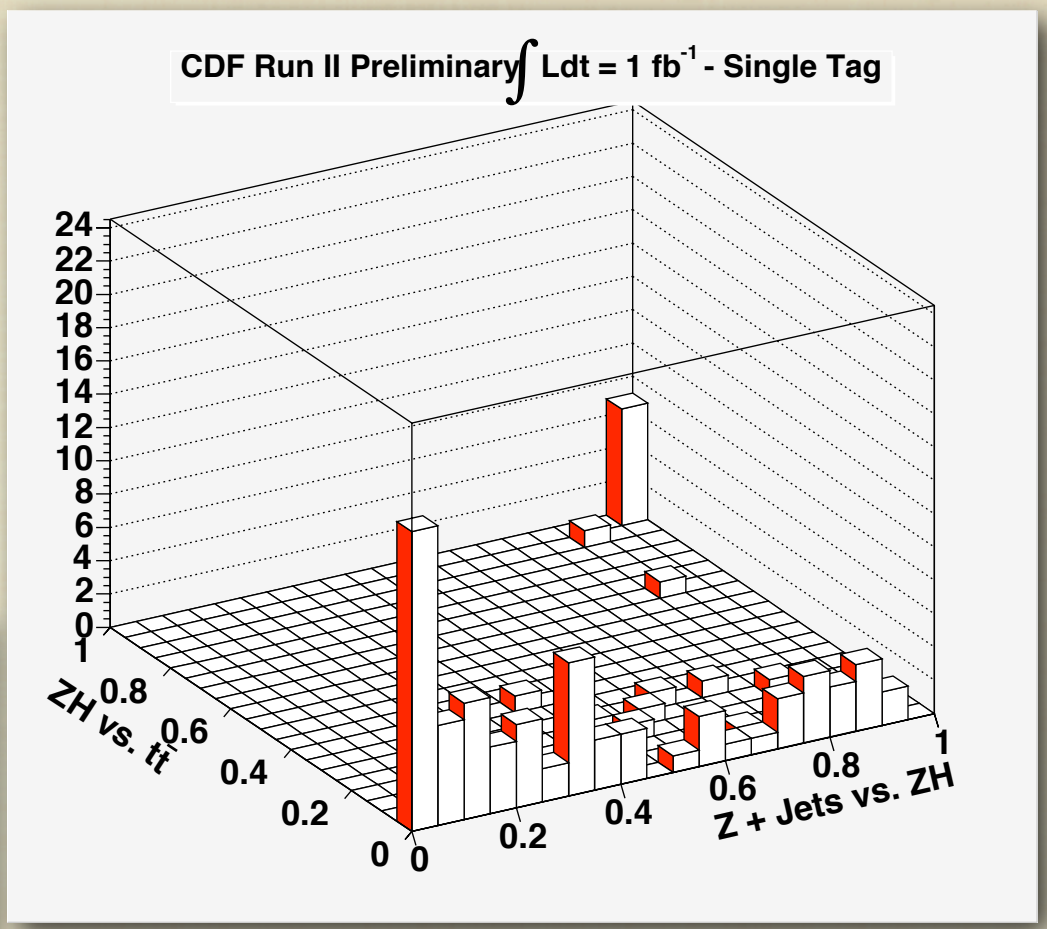


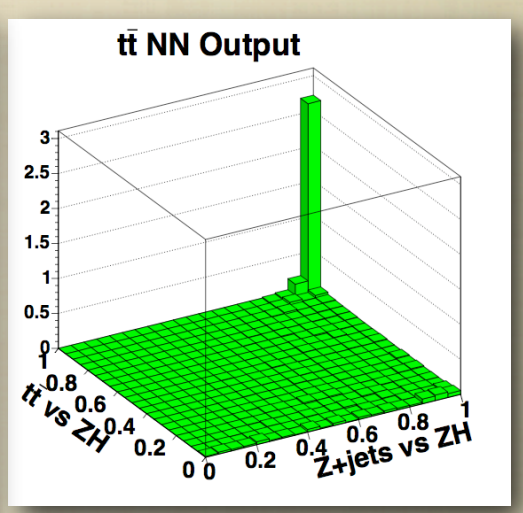


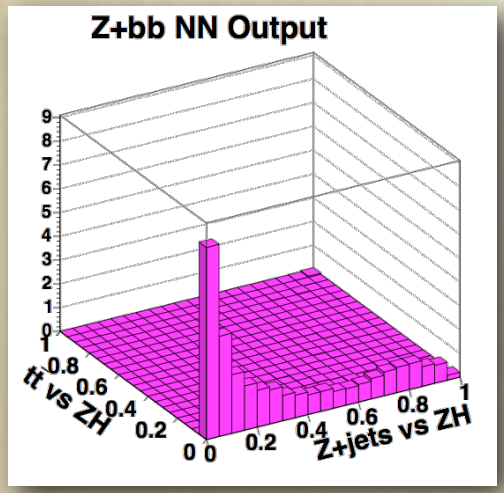


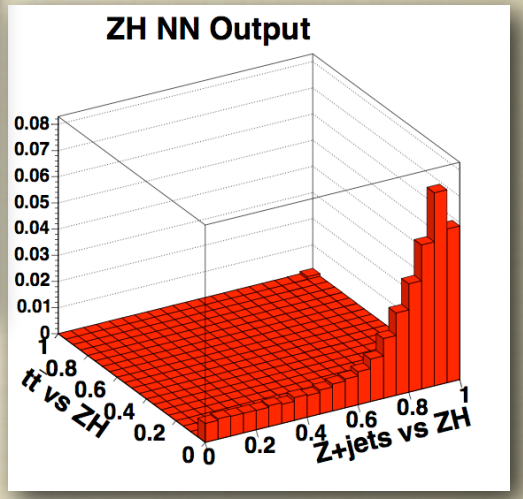
NN models control regions well

Signal region: data with one b-tag





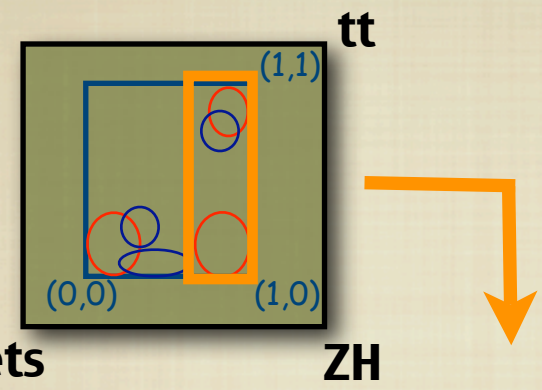


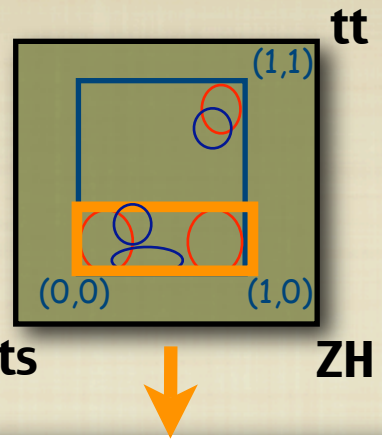


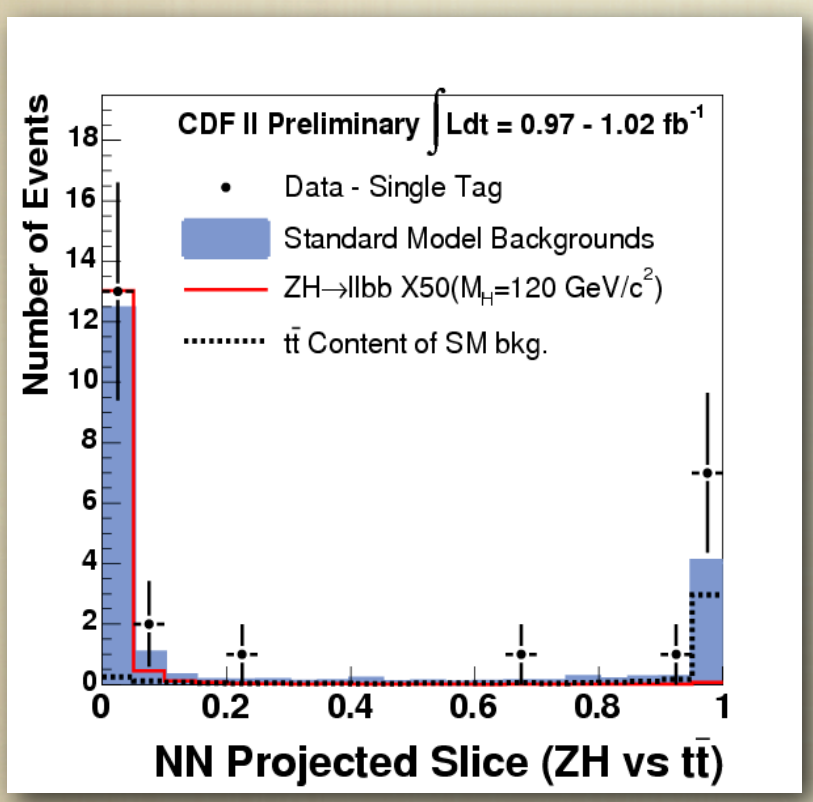
Expected : 101.6 +/- 17.8

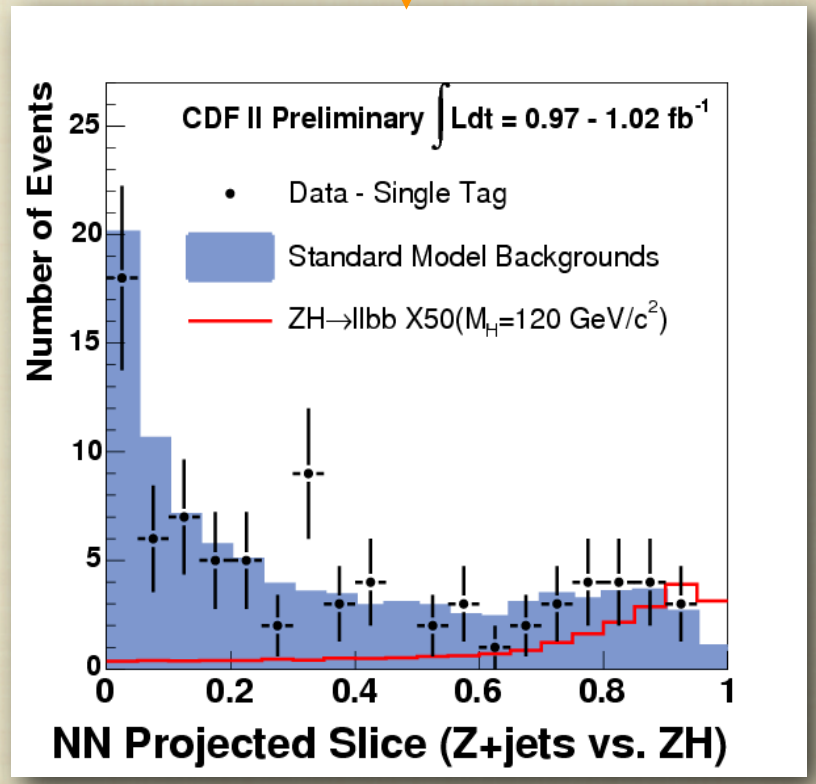
Data : 100 events

Signal region : data with one b-tag

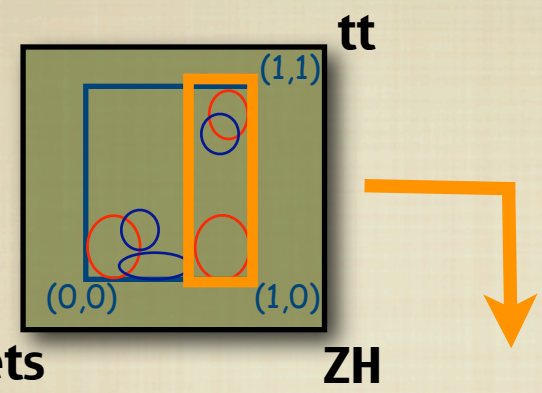


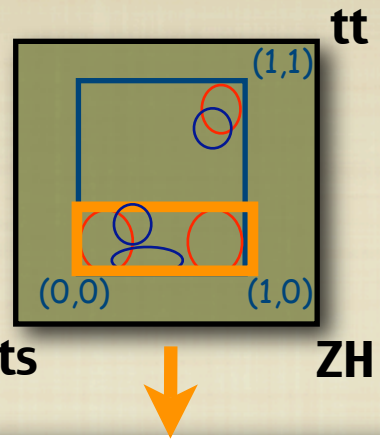


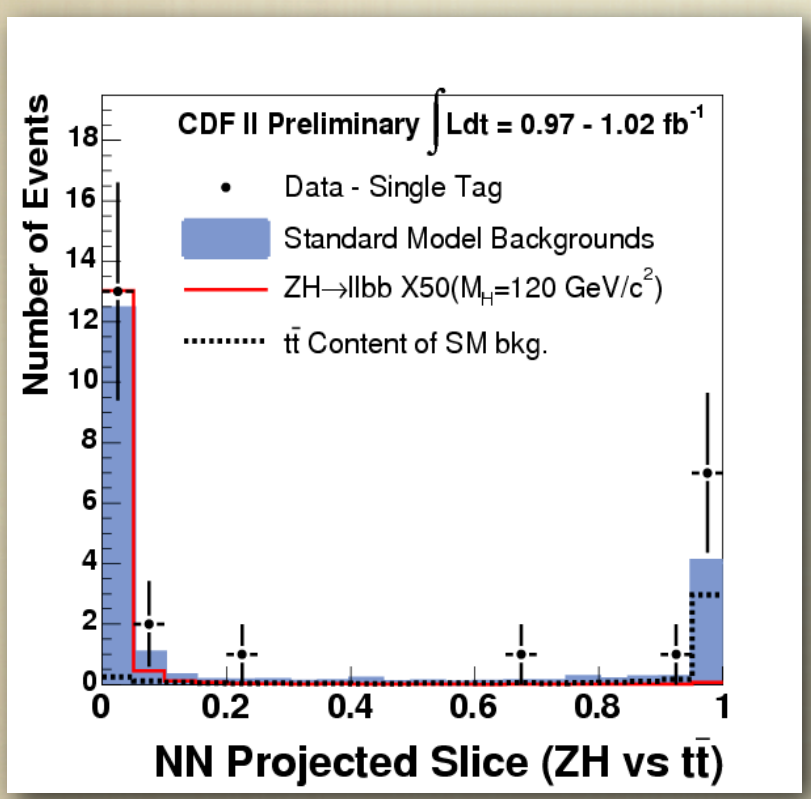


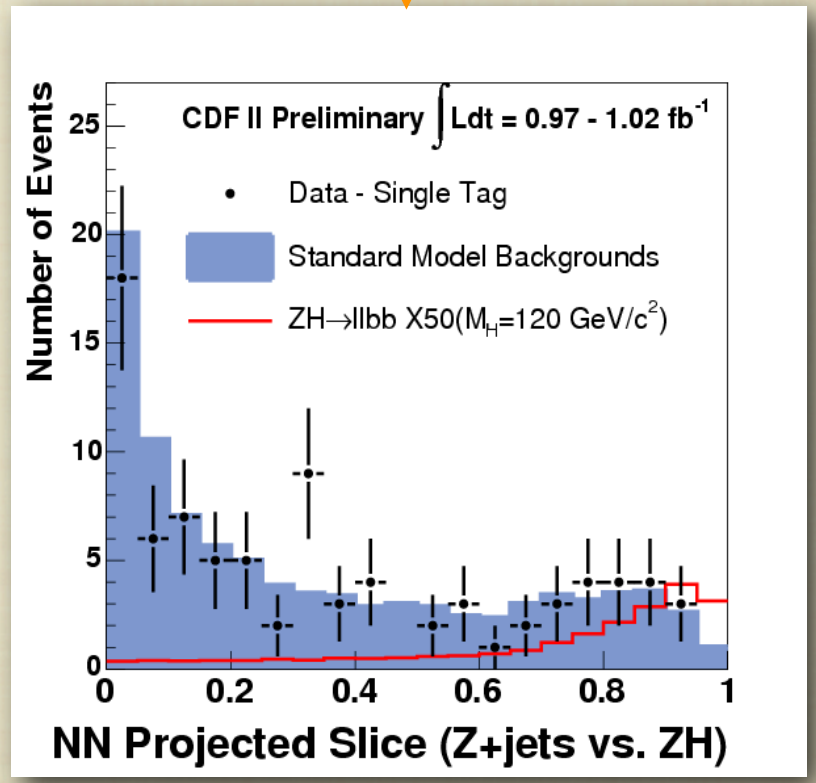


Signal region : data with one b-tag



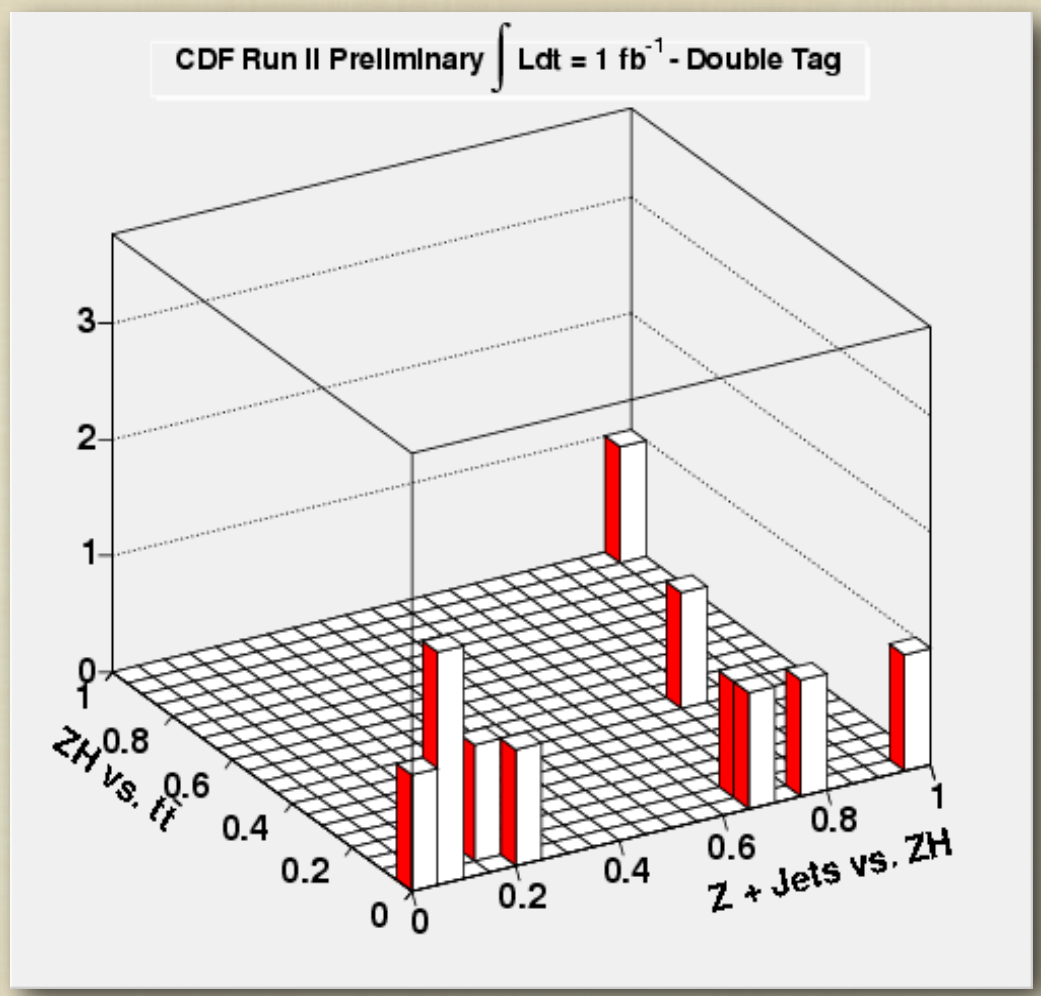


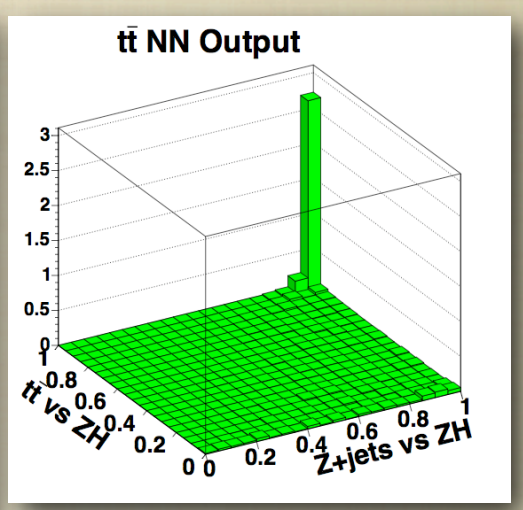


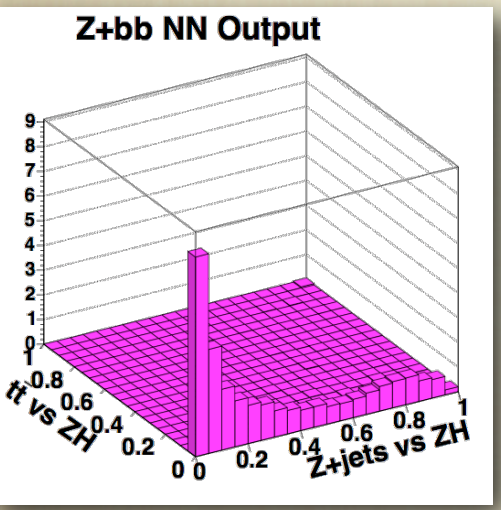


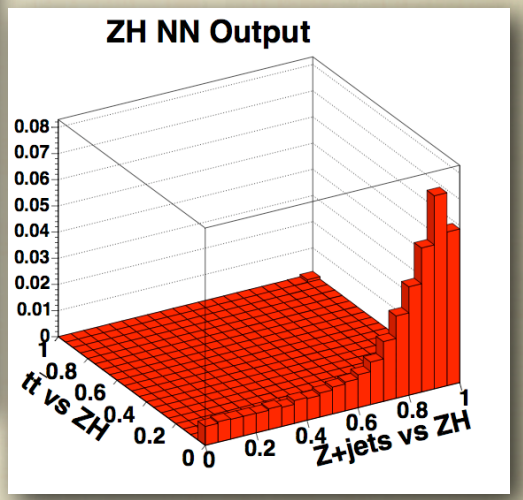
tt cross section can be fit simultaneously in future

Signal region : events with two b-tags





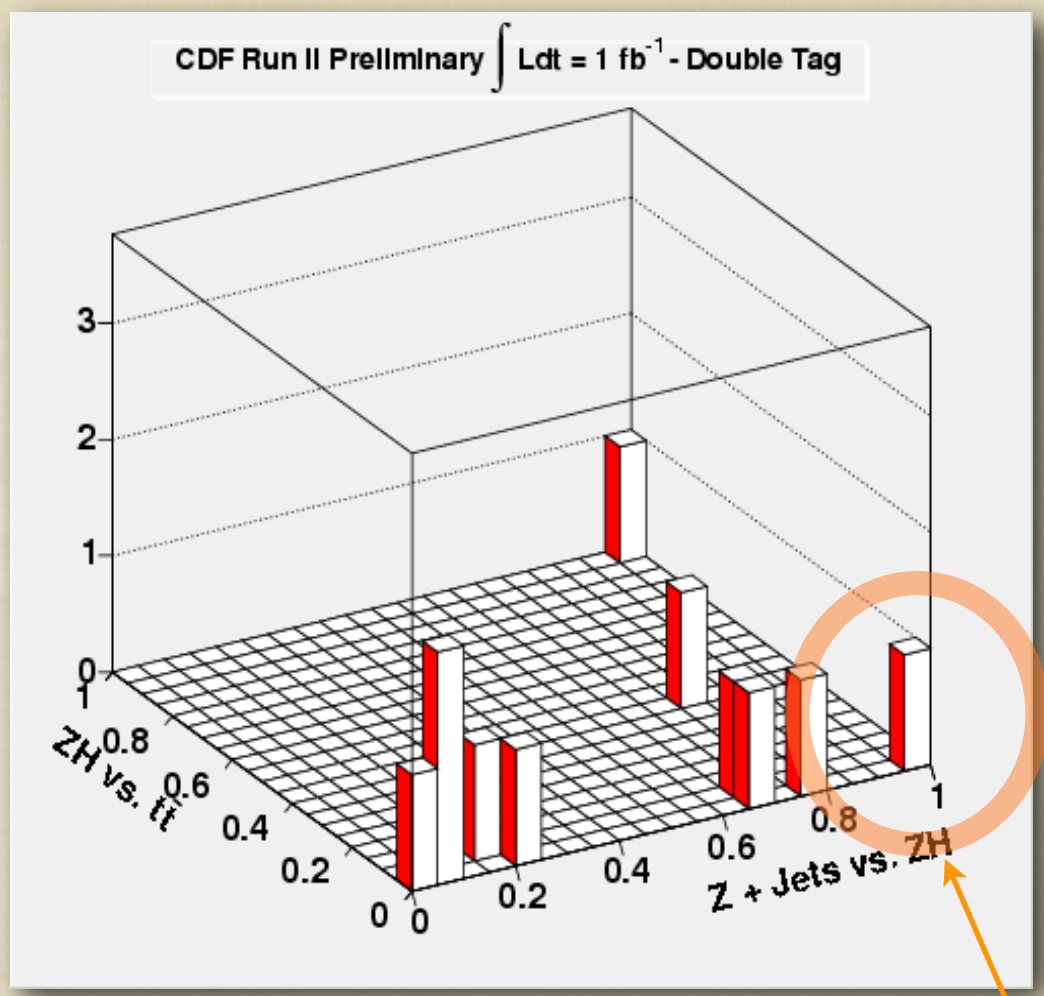


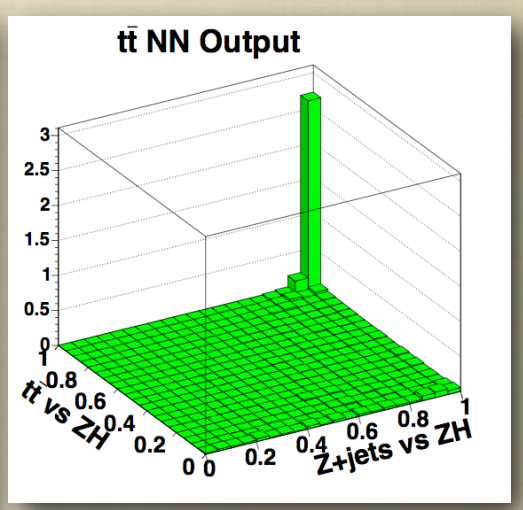


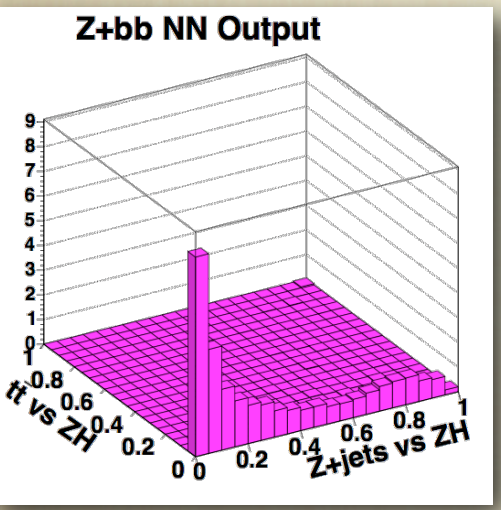
Expected : 12.8 ± 3.5

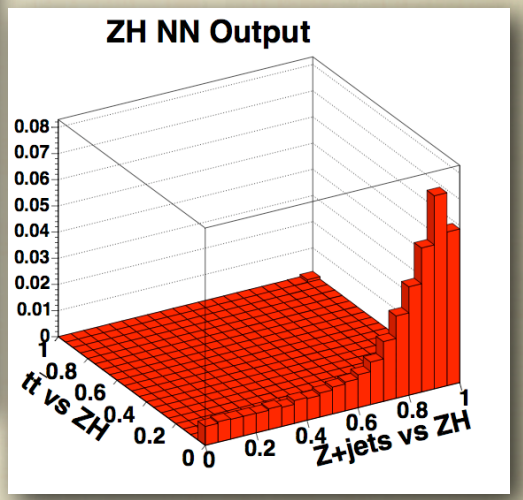
Data : 11 events

Signal region : events with two b-tags





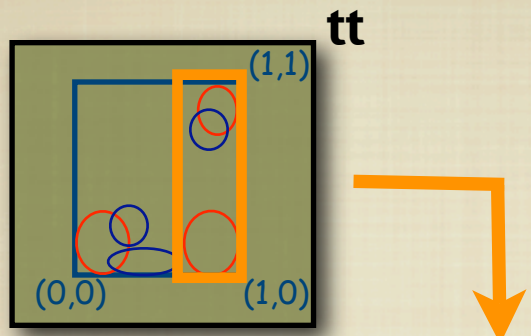


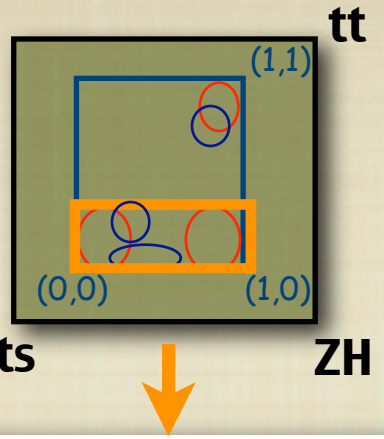


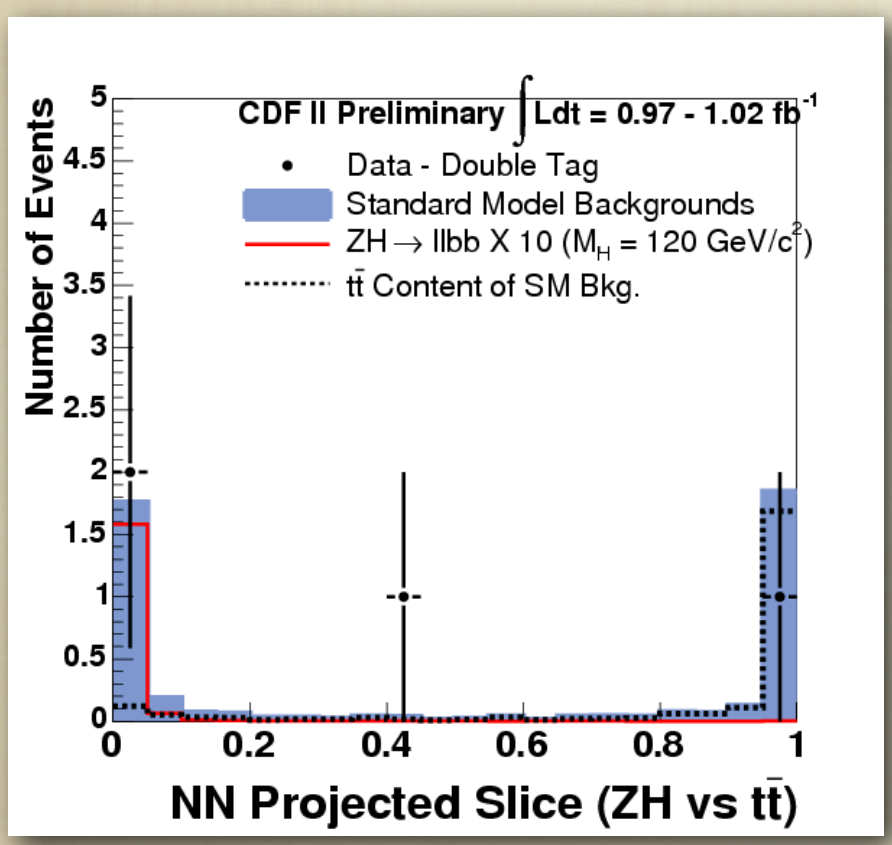
Expected : 12.8 ± 3.5
Data : 11 events

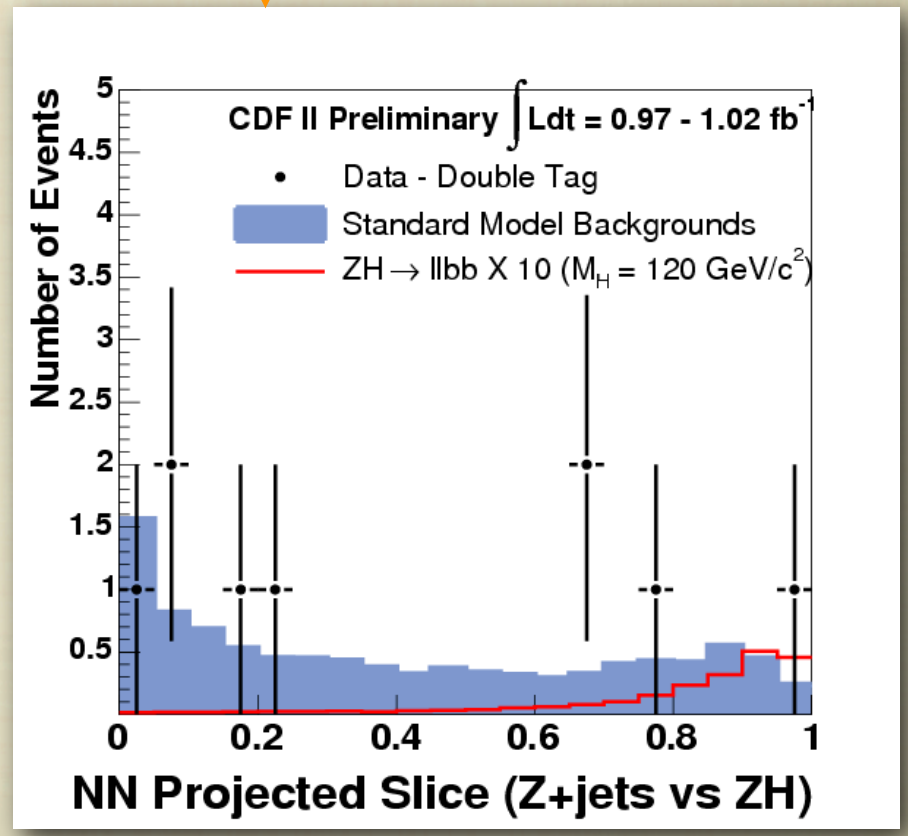
Event in most signal-like bin

Signal region : events with two b-tags



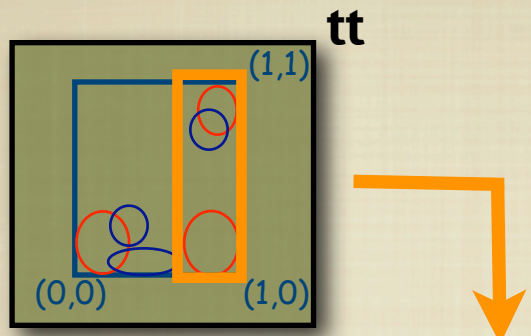


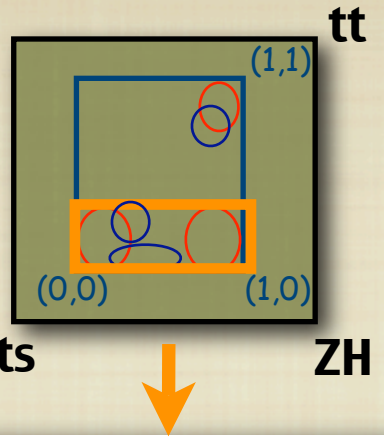


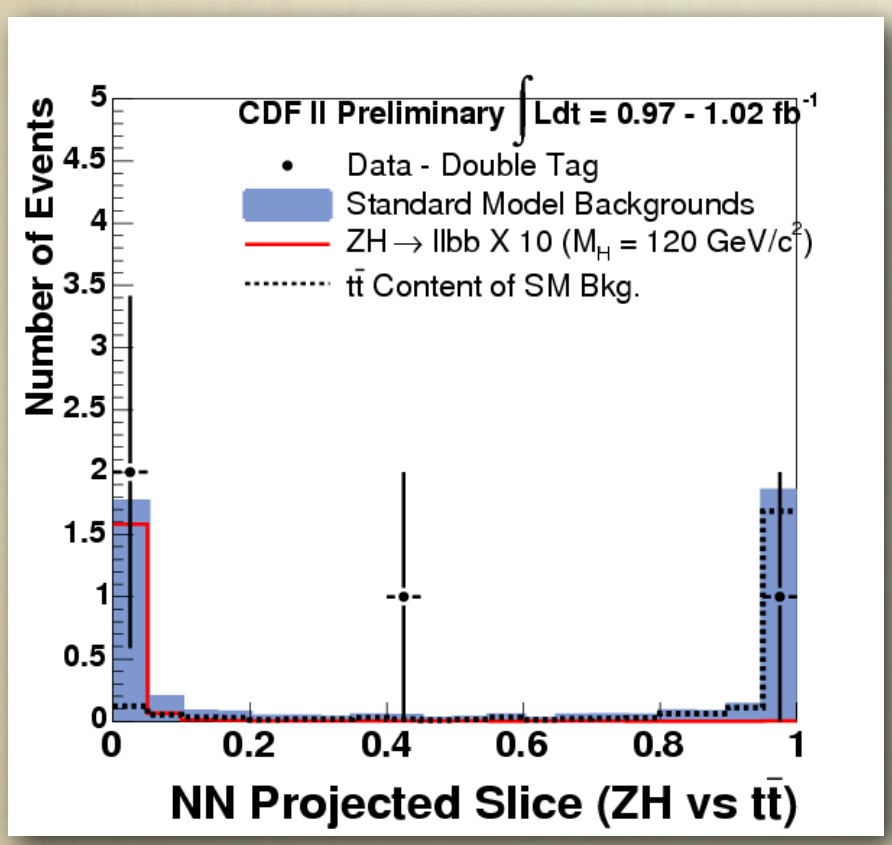


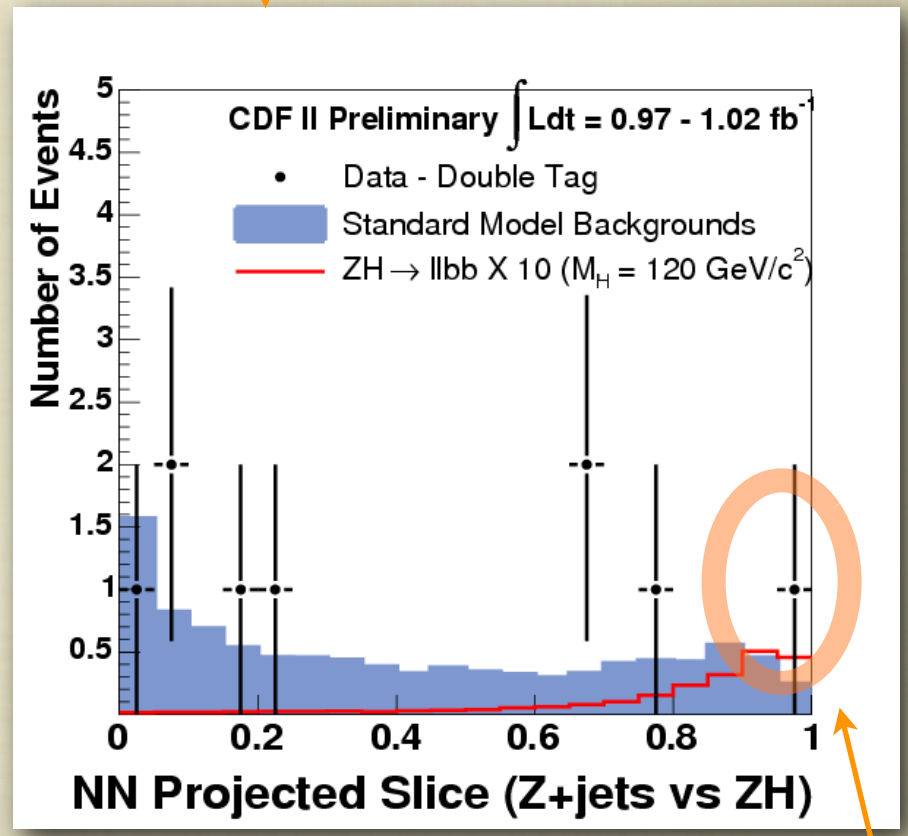
Note: ZH times 10 here

Signal region : events with two b-tags









Note: ZH times 10 here

Remember, we started with 5: 100,000,000,000,000

IN BEST NN BIN WITH TWO TAGS

Higgs events : Everything else

in most signal-like bin **0.042 : 0.18**

Remember, we started with 5: 100,000,000,000,000

IN BEST NN BIN WITH TWO TAGS

Higgs events : Everything else

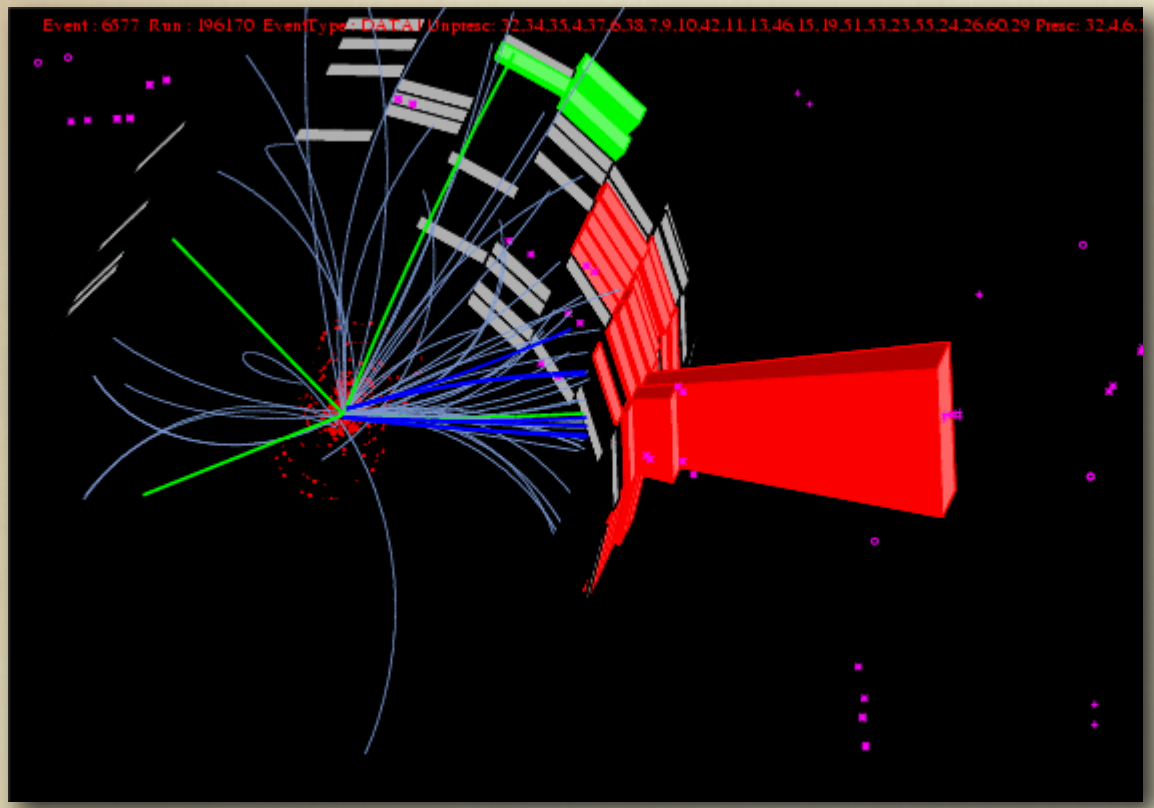
in most signal-like bin **0.042 : 0.18**

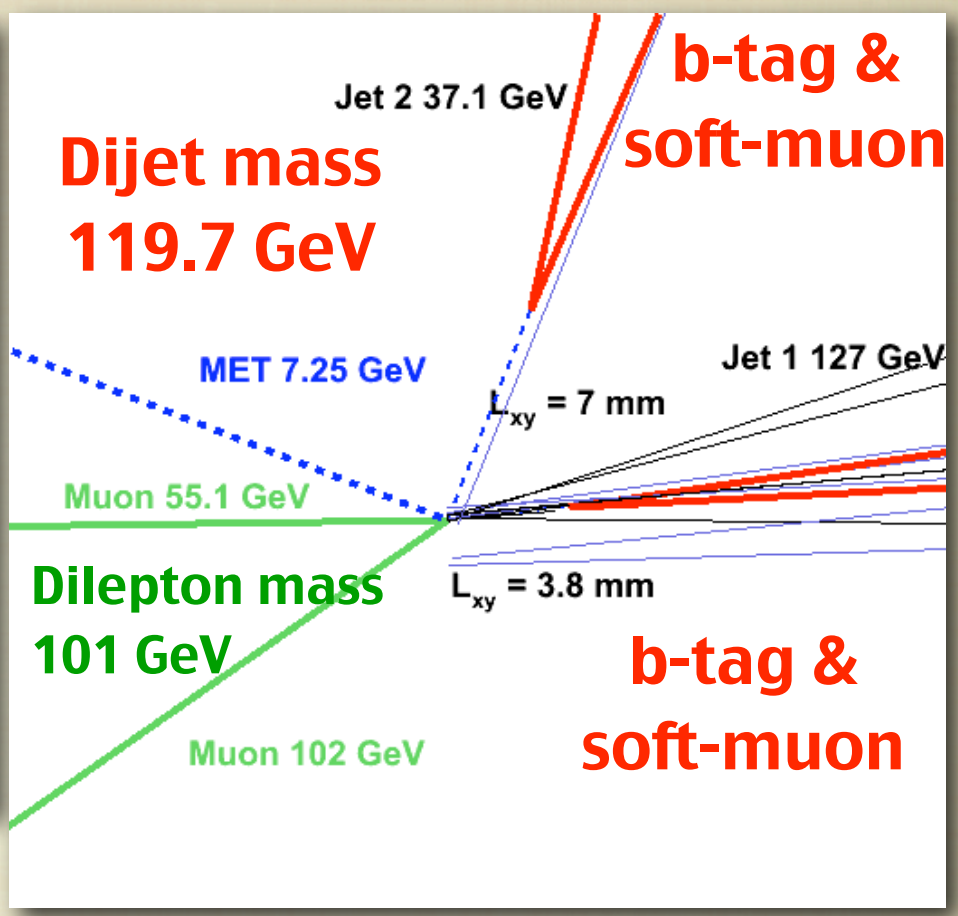
S:B = 1:4

and there's an event !

Higgs candidate S:B = 1:4

RUN 196170 EVENT 6577





Background in this bin

60% Z+bb

11% tt

9% Z+cc

9% ZZ

5% Z+qq (light)

Higgs ~ 2 times tt

Putting it all together

- **We search for ZH contribution in all bins of 2D NN output in 1 b-tag and 2 b-tag data**

CDF II Preliminary, $1\,fb^{-1}$

$1\ fb^{-1}$ dataset	Events with 1-tag	Events with 2-tags
Expected (w/ no SM Higgs)	101.6 ±17.8	12.8 ± 3.5
Data	100	11
SM Higgs Signal	0.5	0.2

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We currently observe no significant excess

Putting it all together

- No significant excess with 1 fb^{-1}
- We proceed to fit all bins of 2D NN data output for the maximum ZH cross-section contribution
  - So-called "upper limit"
  - One-tag and two-tag samples fit independently
  - Use Monte Carlo shapes for ZH, tt, Z+bb, Z+cc, ZZ, ZW
  - Use Data shapes for Fake Z, Z+fake b-jets
- Fit code called "mclimit" (from Tom Junk)
  - Produces upper limit of σ_{ZH} in data
  - Produces expected limits by fitting pseudo-data from background-only model
  - Fit code handles both correlated and uncorrelated systematics

Systematic uncertainties

Results in 14% increase in expected limit

- Largest systematic uncertainties are those which affect signal acceptance
  - 12% from b-tag efficiency uncertainty (from difference between Monte Carlo and data)
    - Uncertainty per jet: hurts two-tag sample more
  - 7% from luminosity uncertainty
- Next largest systematic
  - 6% due to 40% uncertainty on Z+bb and Z+cc
- Other systematic uncertainties considered – small
  - Jet energy scale (acceptance & shape change)
  - Fake b-tag rate
  - ZZ, ZW, tt cross-section
  - Z+jets MC generator (shape change)
  - Parton distribution functions & initial/final state radiation (acceptance & shape change)
  - Lepton ID
  - Charm tagging efficiency

Results

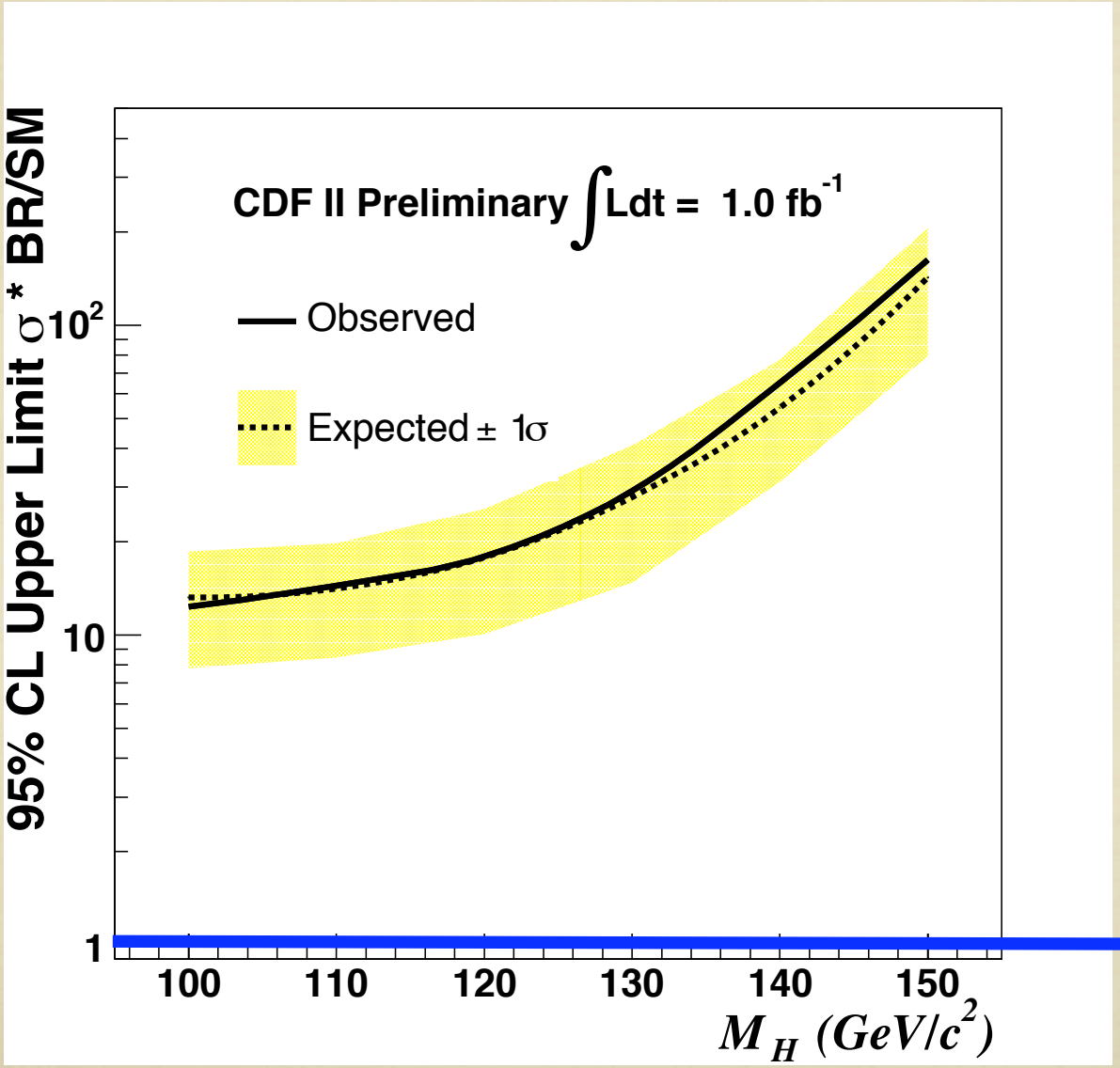
- 95% CL upper limits on $\sigma_{ZH} \bullet BR(H \rightarrow bb)$ for m_H = 115 GeV

Limits CDF II Preliminary, $1\,fb^{-1}$

1 fb^{-1} dataset	1-tag	2-tags	Combined
Observed (expected)	2.3 pb (2.2 pb)	1.9 pb (1.8 pb)	1.3 pb (1.3 pb)
As ratio of upper limit / SM expected cross-section	28 (27)	23 (22)	16 (16)

Limit as a function of mass

- 95% CL upper limits on Higgs cross-section



σ/SM = 1

means 95% exclusion or ~2 σ evidence

In perspective

- **Compare 95% CL upper limit to other CDF channels**

Limits CDF II Preliminary, $1fb^{-1}$

m_H = 115 GeV	ZH → llbb	ZH →vvbb	WH →lvbb	H →WW
$\sigma_{U.L.}$ @ 95% CL observed (expected)	16 * SM (16)	22 * SM (14)	26 * SM (17)	>50 * SM (>50)°

°For m_H = 160 GeV, H →WW is 3.4*SM (4.8)

In perspective

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ZH → llbb is most sensitive CDF channel at m_H = 115 GeV

- **Combined 1 fb^{-1} CDF expected limit is ~9*SM**
  - **Ideas used in this channel will also improve other channels**
  - **All analyses will update with improvements and more data**

Future for ZH → llbb

- More data
  - Statistical scaling alone :

    Limit would be 5 times SM with 8 fb^{-1}
- However, CDF has many other improvements in progress
  - These can also be applied to other Higgs channels
    1. Increased b-tagging
    2. New lepton categories
    3. Looser lepton categories
    4. Tau lepton channels
    5. Specialized & secondary triggers
    6. Further jet energy resolution improvements
    7. Matrix element discriminants incorporated
    8. Reduction of systematic uncertainties
- Each factor is incremental, but :
  - for instance, $1.25^8 = 6$, taking CDF ZH → llbb to 2 times SM

Conclusions

- Retained as much signal as possible
  - Looser lepton selection gave us 1.7 times data equivalent
  - Splitting 1-tag and 2-tag data gave us 1.5 * X
- Narrowed Higgs resonance compared to backgrounds
  - Improving M_{jj} resolution gave us 1.3 * X
- Used multivariate approach to get best signal separation from background
  - Using 2-D Neural Network gave us 2 * X
- All together, gained a factor 7 times more data

Many other improvements and more data coming later this year

Combined with similar improvements to other channels (work ongoing), we're going to be close to finding the Higgs at the Tevatron !